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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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NORTH AMERICAN NATURAL BRIDGES, WITH A DISCUSSION OF THEIR ORIGIN[1]

BY HERDMAN F. CLELAND

(Presented before the Geological Society December 29, 1909)

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[1] Manuscript received by the Secretary of the Society February 9, 1910.

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Introduction, with Definition

There are few topographical features that excite greater interest than natural bridges. This is due, no doubt, to some extent to their rarity and to some extent to the questions which arise as to the force or forces which have been at work to produce such structures. Although rare, the total number on the North American continent is quite large. In this paper, which does not include a description of all the natural bridges of North America, thirty-eight are mentioned.

The terms "natural bridge" and "natural arch" have been so often used as synonyms, both in common parlance and in scientific literature, that it will be necessary to define the terms. In the restricted sense in which the term "natural bridge" is used in this paper, a *natural bridge is a natural stone arch that spans a valley of erosion. A natural arch* is a similar structure which, however, does not span an erosion valley. It will readily be seen from the above definitions that many of the arches which are formed by wind-blown sand, frost, solution, and wave action are not strictly natural bridges.

The classification used in this paper is one based entirely on origin, since all others that have been considered lead to more or less confusion.

A. Natural Bridges initiated by Stream Erosion

1. *By the perforation of the neck of an incised meander*

Some of the most imposing of the world's natural bridges were formed by the undercutting on the inside of the curve of an intrenched meander

FIGURE 1.—ROCK BRIDGE ACROSS SWIFTS CAMP CREEK, NEAR CAMPTON, KENTUCKY
Formed by the perforation of an incised meander. (See text figure 1)

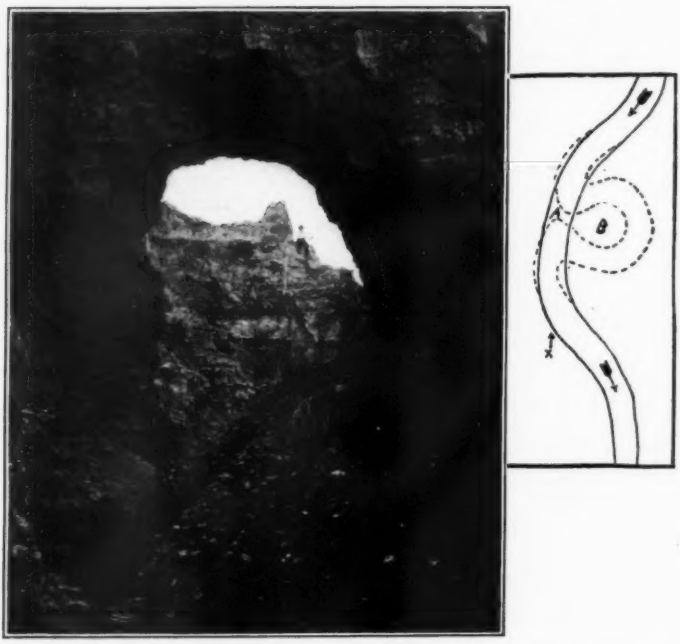

FIGURE 2.—NATURAL BRIDGE IN BAD LANDS OF SOUTH DAKOTA
This bridge, which is south of White River below the mouth of Porcupine Creek, was formed by the perforation of an incised meander. Photograph by Mr. Barnett from point "x."

until at length an opening was made which permitted the water of the stream to cut off its meander by passing under the arch thus made.

a. Rock bridge across Swifts Camp Creek, Campton, Kentucky.—The so-called "Rock Bridge" near Campton, Kentucky (plate 18, figure 1), furnishes an excellent example of a bridge of this origin. This bridge was visited by the writer in July, 1909, and is described here for the first time. It is situated in the floor of a narrow valley from 125 to 150 feet deep, and is composed of a coarse red sandstone which is almost conglomeratic in some portions. The top of the bridge is between 15 and 20 feet above the surface of the stream; the length of the span is 50 feet and the width varies from 6 to 12 feet. The thickness of the arch is about 8 feet.

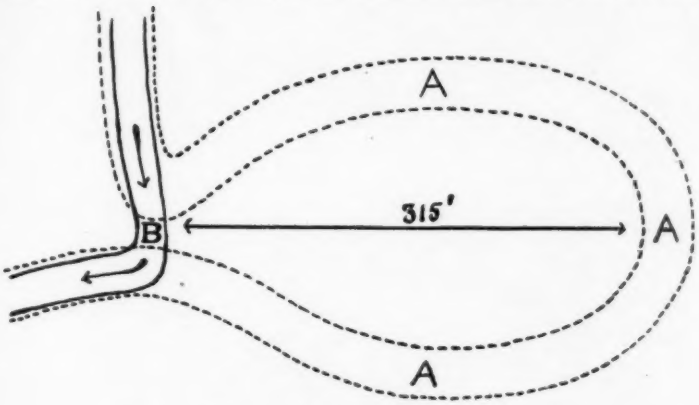

FIGURE 1.—*Diagram indicating Origin of Rock Bridge*

It will be seen from the accompanying diagram (figure 1) that the abandoned meander is long for its width, and that the sharp curve which the stream formerly made was such as to produce rapid cutting on the inside of the curve. The abandoned meander is now filled with alluvium and is cultivated. The cause of the meandering seems to have been the finding of a more resistant stratum by the stream in its downward cutting. It is possible, however, that a temporary baselevel was reached by a halt in the elevation of the region, by temporary lowering of the land, or by some temporary dam.

b. South Dakota bridge.—This bridge (plate 18, figure 2), located south of White River below the mouth of Porcupine Creek, in the Bad Lands of South Dakota, and formed of White River beds, is described by Barnett[2] as follows:

[2] Journal of Geology, vol. xvi, no. 1, January to February, 1908, pp. 93-95.

"The opening of the archway is about 12 feet high by 8 feet wide, and the thickness of the arch is something like 10 feet in a vertical direction by 7 feet in a horizontal. The gorge is about 30 feet deep, with almost vertical walls. The rock is a hard, rather blocky, light blue clay, showing typical bad-land topography."

FIGURE 2.—*Pont d'Arc (Ardèche)*

Scale, 1:400,000. The origin of the bridge is evident from the map

The origin of the bridge can be readily understood by a study of the figure, which, with the illustration (plate 18, figure 2), is reproduced from the article cited.

FIGURE 1.—THE EDWIN NATURAL BRIDGE, SAN JUAN COUNTY, UTAH

Photograph of a painting by H. L. A. Culmer. (See also text figure 4.) Height, 111 feet; span, 205 feet; width, 30 feet; thickness of arch, 10 feet

FIGURE 2.—THE AUGUSTA SANDSTONE NATURAL BRIDGE, SAN JUAN COUNTY, UTAH

Photograph of a painting by H. L. A. Culmer. Height, 265 feet; span, 320 feet; thickness, 83 feet; width, 35 feet

c. Bridge at Attica, Indiana.—A natural bridge over which a roadway passes, said to be about 30 feet in height from the stream bed to the top of the bridge, spans Bear Creek near Attica, Indiana. From the very imperfect description of the bridge, which it has been possible to secure by correspondence, it appears that this bridge was formed, as in the case of the Campton bridge, by the stream tunneling through the isthmus of the incised meander.

d. Pont d'Arc, France.—A discussion of natural bridges formed by the perforation of the isthmus of incised meanders would be incomplete without a mention of the famous Pont d'Arc across the Ardêche River, in east central France.[3]

This, the most imposing natural bridge in Europe, has a height of about 60 meters and a width of 65 meters and is composed of a horizontally bedded limestone. The size of the cavity is due both to the deepening of the valley and, after the hole was made, to the crumbling of the interior surface of the arch by the agencies of the weather.

Früh includes this bridge in his division B, I, "Limited to easily soluble rocks (carbonates and sulphates)." The fact that bridges of sandstone are formed by the perforation of the neck of an incised meander, shows that mechanical erosion and not solution, as Früh supposes, is the important agent in the formation of bridges of this type. Solution is probably a negligible factor. A glance at the map (figure 2) of the region in the vicinity of Pont d'Arc shows the origin to be as described above.

e. Bridges of Southeastern Utah.—Probably the largest and most impressive natural bridges in the world are those which have been described from San Juan County, Utah. These bridges may be reached either from the north, by leaving the Rio Grande and Western Railroad at Thompson Springs, thence by stage to Moab and Bluff; or, by leaving the Denver and Rio Grande Railroad on the east, going by stage to Cortez and Bluff. The three best known bridges are about 65 miles northwest of the latter village.

The courses of the streams in this region, as described by H. L. A. Culmer (the artist who painted the pictures illustrated in this article, plate 19, figures 1 and 2), are very suggestive:

"The windings of Grand Culch [for example] are such that in one place we find ourselves separated by a wall only 60 feet in thickness from the spot we left some time before, although we have since traveled nearly a mile."

[3] J. Früh: Über Naturbrücken und verwandte Formen ect. Jahrbuch der Naturwissenschaftlichen Gesellschaft (St. Gallen, 1905), p. 368.
Reclus: The earth and its inhabitants, vol. II, Europe, pp. 96-97.
Martel: Les Cervennes, p. 291.

In the walls of these canyons, which are said to be from 400 to 1,000 feet deep, are numerous cliff dwellings, many of which are in an excellent state of preservation, together with hieroglyphics, pottery, and stone and bone implements.

The streams rarely have water in them after April, except at the time of rains and cloudbursts, at which time their erosive power must be great, since the volume of water is very large. It is reported that there is evidence that in places the water reaches a depth of 100 feet.

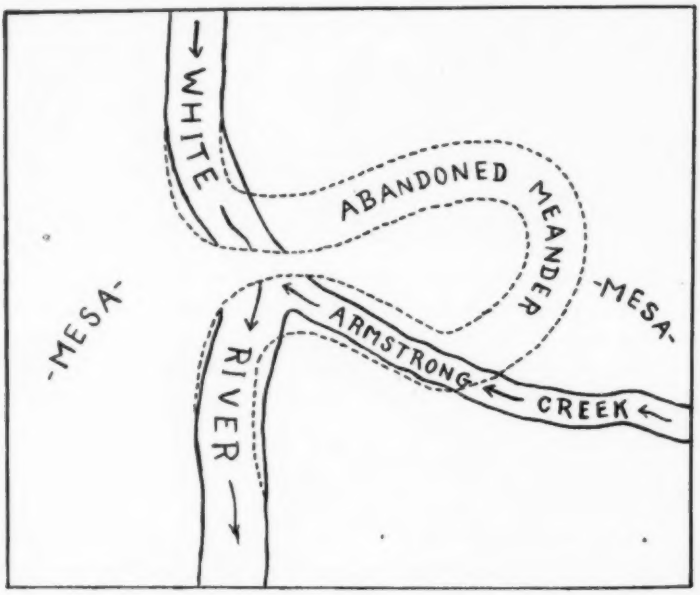

FIGURE 3.—*Diagram showing Origin of the Caroline Natural Bridge, Utah*
Modified from diagram by H. L. A. Culmer in a letter to the writer

The rock of which the bridges are composed is a buff to dull red Triassic (?) sandstone; horizontally bedded and often strongly cross-bedded. The three bridges which have been so often described, the Edwin, Caroline, and Augusta, are within three miles of each other. A fourth bridge, called Nonnezoshi, northwest of Navajo Mountain, and about 50 miles southwest of the above, discovered by Utah Archæological Expedition last summer (1909), has a length of 273 feet and a height of 308 feet, making it, as far as known, the largest natural bridge in the world.

Since the writer has not visited this region, and consequently has not made a study of the bridges on the ground, his conclusions are necessarily based on the observations of others. In the case of the Caroline bridge, the mode of formation seems to be the same as that of the foregoing bridges, judging from the rough sketches of the region submitted to the writer, one of which is produced here (figure 3). It is possible that in this case the perforation of the neck of the meander was hastened by the work of Armstrong Creek.

The Edwin bridge (plate 19, figure 1) offers a variation from the type already discussed, as will be seen by the accompanying diagram (figure 4).[4] The neck of land perforated was not a meander, but a narrow strip of land at the juncture of two streams. It appears from the evidence

FIGURE 4.—*Diagram showing Origin of the Edwin Bridge, Utah*
Modified from diagram by H. L. A. Culmer in a letter to the author

that the perforation was made by the lateral cutting of the former Edwin Creek by Armstrong Creek or by a combined action of the two.

The information concerning the Augusta (plate 19, figure 2) and Nonnezoshi bridges is very incomplete, but from what could be gathered from those who had visited them, and also from the fact that the bridges are composed of the same material as the Edwin and Caroline bridges, and are situated in a region of incised meanders, it seems probable that they were formed in the same manner as the Edwin and Caroline bridges.

[4] These diagrams are from rough sketches made by Culmer to show in general the courses of the present and former streams, and are not drawn to scale.

W. W. Dyar: Century Magazine, vol. 68, August, 1904.

H. L. A. Culmer: Technical World, September, 1908, pp. 49-55.

Letters to the writer from Mr. H. L. A. Culmer, 1907.

Other descriptions have appeared in the Sunday supplements of several daily papers, the National Geographic Magazine, Scientific American, Collier's.

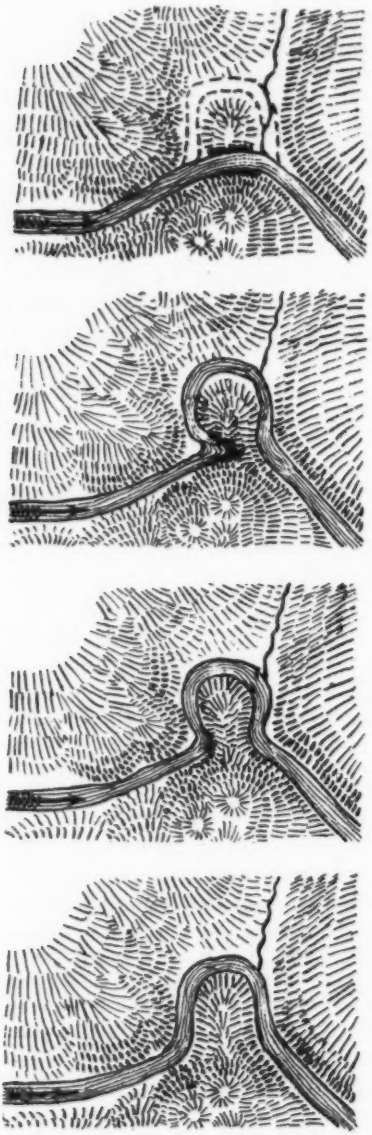

FIGURE 5.—*Maps showing Location of present and former Channel of the Washita River, Oklahoma, after Gould*

Prof. C. N. Gould, in a letter to the writer, states that a natural bridge which probably spanned the river when the rock of the meander was first cut through has disappeared.

f. Bridges of Le Perle Creek, Wyoming, and Buffalo Gap, South Dakota.—The information concerning these two bridges is so meager that nothing can be said of their origin except that they should possibly be included in this group. The Le Perle Creek bridge is composed of "Tensleep sandstone, a white massive formation, moderately hard and presumably with siliceous cement; the span is about 35 feet, the greatest height 10 feet, and the width about 25 feet."[5]

The Buffalo Gap bridge is composed of "Unkpapa sandstone, fine grained, massive, pinkish in color, and with supposed siliceous cement. The span is about 8 feet and the width 6 feet."[5]

g. Discussion of a former natural bridge of this type in Oklahoma.—Through the courtesy of Prof. C. N. Gould,[6] I am able to use the following series of maps (figure 5) showing the location of the courses of the present and former channels of the Washita River

[5] N. H. Darton in a letter to the writer, February 17, 1907.
[6] A letter from C. N. Gould, January, 1910.

where it crosses the Arbuckle Mountains 8 miles south of Davis, Oklahoma.

"The cliffs on the east side of the stream are from 150 to 300 feet high and are composed of solid limestone. At some point between 'C' and 'D,' as indicated in this map, the stream evidently found a course along a folding plane or joint along the narrowest part of the interposed wall. This condition continued until all of the stream ran through this channel and the old channel was abandoned. Later the bridge which evidently spanned the stream fell in."

2. *BY POT-HOLE ACTION*

Theoretically bridges of small size should result by the enlargement of the diameter of pot-holes near their bottoms until the walls of two or more such holes are worn through, thus permitting the water of the stream to pass under an arch. At Shelburne Falls, Massachusetts, and in many other stream beds, partial bridges of this origin occur, but complete bridges of this type are rare.

a. Bridge spanning Kicking Horse River, British Columbia.—The rock of which this bridge, near Field (plate 20, figure 1), is composed is an impure limestone in which a strong vertical cleavage has been produced, the cleavage being so strong that the synclinal structure of the rock of the ledge is often rendered indistinct.

Formerly a ledge of rock produced a fall or rapid in the river at this place. In the course of time two series of pot-holes were developed (as is shown in the diagram, figure 6), which gradually enlarged, especially near their bottoms, until they finally opened into one another. The openings were small at first and only a small quantity of water poured through, but when the wall was broken through they rapidly enlarged, until now the entire volume of the stream flows under the ledge. The height and width of the bridge (figure 6) are difficult to estimate, because of its irregularity and also because of the great volume of water which pours through and fills the opening. The average width of the arch is about 10 feet and the length between 5 and 8 feet. The height of the top of the bridge above the stream is in places not more than 3 feet and the thickness of the arch is probably between 6 and 8 feet.

b. Lamoille River Bridge, Vermont. — A bridge which spans the Lamoille River at low water (shown in the accompanying illustration, plate 20, figure 2) appears to have been formed by pot-hole action, judging from the information furnished by Mr. M. A. Gibson.[7] The width of the ledge through which the opening has been made varies from 6 to 10 feet. The mica schist of the stream bed is full of pot-holes, both

[7] M. A. Gibson in a letter to the writer, 1906.

above and below the bridge, some of which are very deep. The water flows under the ledge (plate 20, figure 2) between "1" and "2." At "3" (upstream) the stream flows over a fall into a basin called the "death pot," and reappears at "4."

3. *EROSION ASSISTED BY FROST ACTION*

a. Yellowstone Natural Bridge.—The origin of the natural bridge across Bridge Creek, Yellowstone National Park, is probably unique, since it is unlikely that the conditions that made it possible have occurred elsewhere.

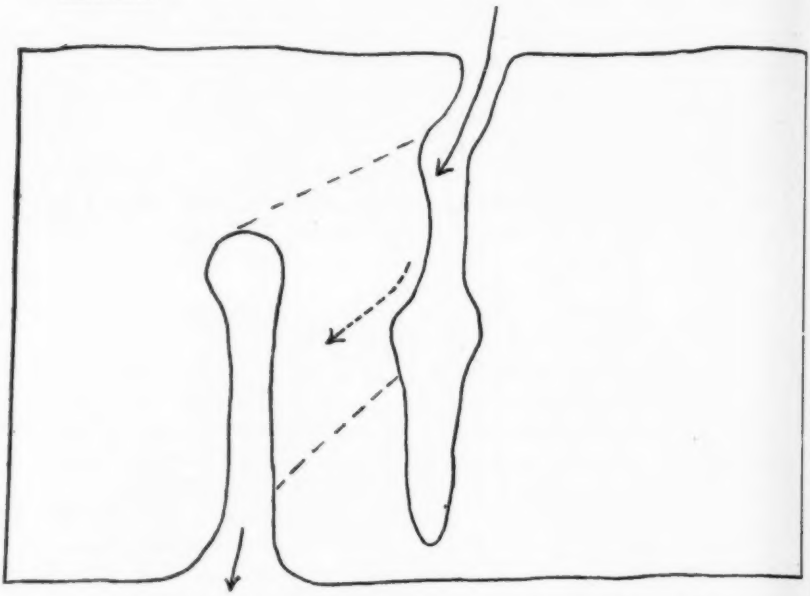

FIGURE 6.—*Diagram of the natural Bridge across Kicking Horse River*
Indicates that the bridge was formed by pot-hole action

The bridge (plate 21, figure 1), which consists of two vertical layers of lithoidal rhyolite, stands 40 feet above the stream bed and has a length of span of about 30 feet. The layers of which the bridge is composed are slightly curved and are separated by open crevices with roughened scoriaceous walls (plate 21, figure 2). Of the two slabs forming the bridge the eastern is 2 feet thick at its ends and thinner in the middle; this is separated from the western slab, which is 4 feet in thickness by a space of about 2 feet.

FIGURE 1.—THE NATURAL BRIDGE ACROSS THE KICKING HORSE RIVER, NEAR FIELD, BRITISH COLUMBIA, SEEN FROM BELOW

(See text figure 6)

FIGURE 2.—THE NATURAL BRIDGE WHICH SPANS THE LAMOILLE RIVER, VERMONT, AT LOW WATER

The water flows under the ledge between 1 and 2. At 3 the stream flows over a fall into a basin (called the death pot) and reappears at 4

FIGURE 1.—BRIDGE OF LITHOIDAL RHYOLITE, BRIDGE CREEK, YELLOWSTONE PARK
Photograph by Walcott, U. S. Geological Survey

FIGURE 2.—VERTICAL, PLATY STRUCTURE OF THE RHYOLITE

This structure made it possible for the stream, with the assistance of frost, to make the Yellowstone National Park bridge. Photograph by Iddings, U. S. Geological Survey.

"The explanation of the formation of the bridge is as follows: The stream which flows underneath the bridge has been able to excavate, owing to a former waterfall and the peculiar platy structure of the rhyolite, in which curved layers of extremely different physical texture and friability offered a favorable site for attack by frost and water."[8]

The excavation was accomplished by the water which flowed over the fall (now the top of the bridge) excavating with its sediment the rock at its base, assisted by the separation of the thin plates of lava by the expansion of the water on freezing. This excavating continued until a layer of more porous lava (represented by the space between the slabs composing the bridge) was found, which permitted the water to flow downward into the cave. This process was repeated, thus producing a bridge made of two vertical layers.

b. Remnants of lava stream roofs not included.—The remnants of lava stream roofs are not included as natural bridges, since they are to be classed as arches. It should be stated, however, that arches of this sort perform the functions of bridges, since they permit men and animals to pass over a cavity which otherwise it would be necessary to bridge.

4. *TRAVERTINE-CEMENTED STREAM DEPOSITS UNDERCUT BY STREAM EROSION*

The writer has neither seen nor been able to learn of any bridges of this origin in North America. Professor Früh cites several examples from Europe and South America which should be mentioned here, in order that our classification may be as complete as possible.

a. Bridges in Arcadia and Messina, Greece.—In northern Arcadia, in Greece, a brook disappears under a tunnel 100 meters long whose roof consists of earth and debris cemented by travertine. It supports fields, a few trees, and a roadway.[9]

Another in northern Messina, in Greece, is described as being a tunnel of mountain debris cemented by travertine.

b. Puenta del Incas, South America.—Another cited by the same writer,[10] from Güssfeldt, is near the Bañas del Inca. It is 40 meters long and 40 meters broad and consists of valley debris cemented by travertine over which a compact layer of travertine has been formed.

5. *BY THE UNDERCUTTING OF A PETRIFIED LOG*

An unusual natural bridge (plate 23, figure 1) formed by stream erosion is that in the petrified forest of Adamana, Arizona, where a petrified

[8] H. F. Cleland: American Journal of Science, vol. 20, August, 1905, p. 123.
[9] Früh: Naturbrücken, ibid., p. 363.
[10] Ibid., p. 363.

log of agatized wood has been undermined by stream erosion until it now spans a true valley of erosion. The canyon or gulch has a north direction and is very precipitous, beginning only 200 yards above the bridge and rapidly broadening in its descent. At the point where the bridge crosses the canyon it is about 30 feet wide, but the trunk lies diagonally across and measures 44 feet between the points at which it rests on the sides of the canyon. The canyon is here about 20 feet deep. The total length exposed is 111 feet, so that more than 60 feet of the upper part of the tree lie out on the left bank of the canyon. At about the middle of the canyon the tree measures 10 feet in circumference, which implies a diameter of over 3 feet. The rock in which the log was imbedded is very soft and easily eroded. The Santa Fe Railroad Company has placed two piers (shown in the illustration) under the bridge to support it. These supports are, however, of little use and are very unsightly.[11]

6. *BY THE HEADWARD CUTTING OF TWO STREAMS*

Certain natural bridges near the station Natural Bridge, in Powell County, Kentucky, near the middle fork of Red River, should be discussed here because of their peculiar erosional origin. The country in which they occur is a high plateau region, in a mature stage of development (plate 22, figure 2), composed of heavy bedded strata of carboniferous sandstones and limestones, which have been deeply dissected by stream erosion, forming deep valleys with divides, which in many places are only a few feet wide. The bridge from which the station Natural Bridge received its name (plate 22, figure 2) is one of these and is perhaps the most imposing of them, the arch itself being 32 feet high and the width of the cavity at the bottom being about 66 feet. The width of the span is 20 feet and its thickness is about 12 feet. This arch and two others in this region were formed by the headward cutting of two streams the headwaters of which have almost met (see map, figure 7), leaving a divide which, in the case cited, is but 20 feet in width. The cavity now spanned by the bridge was produced by the combined action on the divide of water, wind and frost. Two other "bridges" occur near the above.

These arches were first described by A. M. Miller,[11a] who gave the correct explanation of their origin.

7. *BY REMOVAL OF UNCONSOLIDATED MATERIAL UNDERLYING A RESISTANT STRATUM*

a. Switzerland. — Unconsolidated material underlying a resistant stratum may be carried away in suspension by water which first seeped

[11] For a discussion of the petrified forest, see "The petrified forests of Arizona." L. F. Ward, Smithsonian Report, 1899, pp. 289-307.

[11a] A. M. Miller: Natural arches of Kentucky, Science, vol. 7, June 24, 1898, p. 845.

FIGURE 1.—THE BRIDGE AT NATURAL BRIDGE STATION, POWELL COUNTY, KENTUCKY
Formed by the headward cutting of two streams. Photograph used by courtesy of the Lexington and Eastern Railroad

FIGURE 2.—CONFIGURATION OF THE COUNTRY NEAR THE STATION NATURAL BRIDGE, POWELL COUNTY, KENTUCKY
Showing the conditions favorable to the formation of bridges by the headward cutting of streams. (See text figures 6 and 7)

FIGURE 1.—A PETRIFIED LOG FORMING A BRIDGE ACROSS A RAVINE IN THE PETRIFIED FOREST OF ARIZONA NEAR ADAMANA

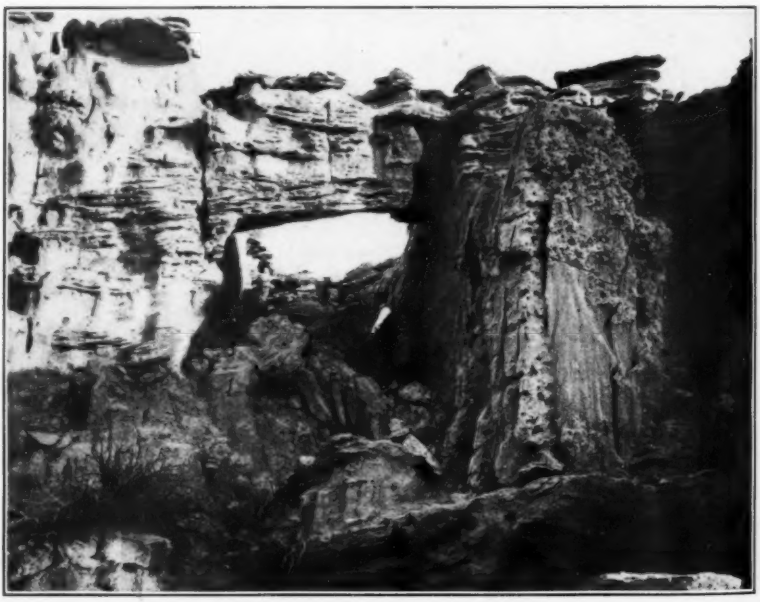

FIGURE 2.—NATURAL BRIDGE, BIG BAD LANDS, SOUTH DAKOTA
Photograph by Darton, U. S. Geological Survey

through a joint or other crack in the harder overlying rock, thus forming a natural bridge. What may be considered a type of this mode of formation is a bridge over the Thur (described by Früh[12]) near Krummenau, in Switzerland. In this region the underlying rock consists of a series of alternating beds of southerly dipping marls, sandstones and

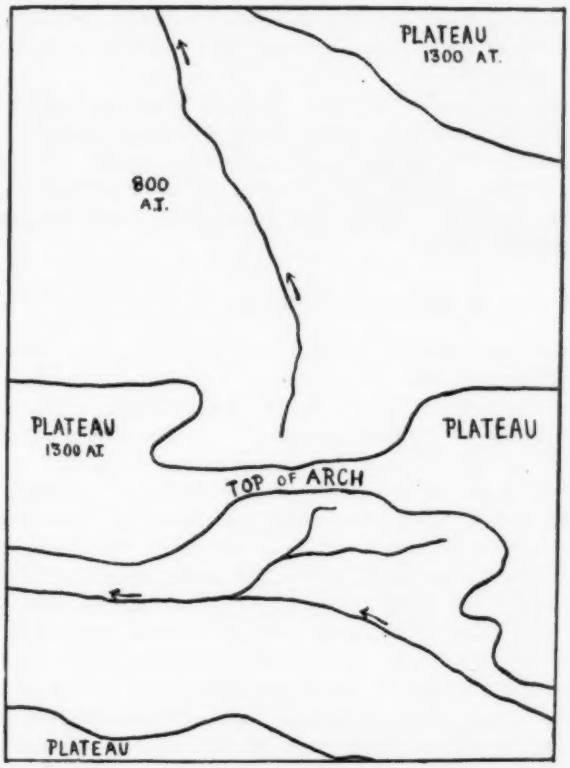

FIGURE 7.—*Map indicating Formation of Natural Bridge in Powell County, Kentucky, by the headward Cutting of two Streams in a Plateau Region*

resistant, fissured conglomerates several meters thick. Keeping these conditions in mind, the formation of the bridge is clear. The river loses itself here and there through fissures in the conglomerate to a layer of marl. Instead of working chemically, the water carries the marl away in suspension, thus leaving a natural bridge or tunnel. Since the stream in

[12] J. Früh: "Naturbrücken," etc., p. 369.

this place has cut through several layers of conglomerates and marls before reaching its present position, it is probable that this process has been repeated several times, perhaps with the formation at different levels of several natural bridges that have since disappeared.

b. Big Bad Lands of South Dakota.—This bridge (plate 23, figure 2) spans the valley of a temporary stream and was evidently formed as described above. It can not, however, be considered a typical example. "The rock consists of a coarse sandstone, rather soft, and apparently with siliceous cement."[13]

c. Earth bridges.—To the above should be added small earth bridges. Such earth bridges occur where a muddy or alluvial valley bottom covered with turf is in process of trenching by head erosion. The low water drainage becomes subterranean, following cracks or joints, along which it develops channels. Such bridges are necessarily very temporary and the streams very small.

B. Bridges initiated by Wave Action

One could cite scores of examples of arches which have been produced by wave action, but few of these should strictly be considered as natural bridges. The natural bridge at Santa Cruz, California (plate 24, figure 1), however, should be so considered, since it does span a valley of erosion. This bridge was described by Shaler[14] as the portion of an arch that has fallen in, the space being widened by the waves which roll beneath the bridge. He states further that the horizontal strata are of limestone and are thus easily soluble by the waves. This latter statement is an error, since the upper part of the bridge consists of Pleistocene deposits a few feet thick resting on horizontal diatomaceous shales of Miocene age. The cavity was excavated by the mechanical action of the waves and not by solution. "This bridge occurs on the edge of a marine terrace and was formed by the waves eating in under the nearly horizontal shale beds forming a cave, the roof of which dropped in behind the bridge, leaving the arch across the entrance."[15] Several of these bridges have been formed at different times along this terrace, but they usually last but a short time. Photographs of two or three are still preserved.[16]

It will be seen that such a structure could be termed either a natural arch or a bridge without going far astray. It has, however, been in-

[13] N. H. Darton in a letter to the writer, February, 1909.
[14] Shaler: Sea and Land, p. 18.
[15] Letter from Prof. J. C. Branner.
[16] Letter from Dr. Ralph Arnold.

FIGURE 1.—A NATURAL BRIDGE IN MIOCENE SHALES, SANTA CRUZ COUNTY, CALIFORNIA
Formed by wave erosion. Photograph by Arnold, U. S. Geological Survey

FIGURE 2.—A NATURAL BRIDGE OF YELLOW SANDSTONE SPANNING A SMALL BROOK ON LOOKOUT MOUNTAIN, TENNESSEE
Formed by the widening of a joint

cluded among natural bridges because the valley which it spans for a portion of the year, at least, probably contains a small stream. The valley can not, however, be said to be formed by stream erosion.

C. Bridges initiated by Solution

In regions in which the surface rock is thick and fairly soluble tunnels as well as natural bridges may be formed, the only difference between a tunnel and a bridge being the greater length of one than the other. Probably the greater number of the natural bridges of the world—though certainly *not the most imposing*—are to be included in this division.

1. *By seepage*

Natural bridges may be formed by seepage through a joint or other crack in the bed of a stream, usually approximately at right angles to the course of the stream, thence along a bedding or other plane and discharging under a fall or rapid.

a. The Virginia Natural Bridge.—This remarkable natural bridge may be considered a type of bridges formed by seepage. In bridges of this character the cavity which later produced the bridge was formed by water percolating through a joint or fissure athwart the stream, thence along a bedding plane and emptying under a fall or rapid of the stream. The channel thus formed was gradually enlarged until all the water of the stream was diverted from the stream bed below the point of ingress, leaving a bridge. The height of the arch of the natural bridge above the stream will naturally depend upon the amount of cutting subsequent to the formation of the bridge, and to the weathering of the under side of the arch. Bridges formed in this way can readily be distinguished from those formed by the caving in of all but a small portion of the roof of a cavern by the fact that the top of bridge of the former was plainly at one time the bottom of the valley.

"On the north side" the summit of the bridge is 236 feet above the water, and this part of the arch has a thickness of 44 feet and a span of from 45 to 60 feet. The western edge is about 10 feet higher and the eastern edge about 10 feet lower than the central point."

b. The Oklahoma Natural Bridge.—A natural bridge of unusual origin occurs 15 miles southeast of McAlester, Oklahoma.[18] The limestone, which is almost vertical in this place, permitted the water of the

[17] C. D. Walcott: National Geographic Magazine, vol. 5, 1893, pp. 60, 61.

[18] The information concerning this bridge was obtained from Prof. C. N. Gould in a letter, January, 1910.

stream to flow down along a bedding plane, thence through a crack or joint from which it issued beneath a fall which existed at the contact of the limestone and a shale. The arch is said to be about 10 feet high above the stream level and probably 25 feet across.

c. The Massachusetts Natural Bridge.—The marble natural bridge at North Adams, Massachusetts, furnishes another illustration. With the possible exception of the Virginia Natural Bridge, that in North Adams (plate 25) is one of the most interesting and unique in the eastern half of the continent. Hawthorne in his *American Note Book* speaks of its beauty and of the pleasure he often took in visiting it. It spans Hudson Brook, a small stream emptying into Beaver Creek, a tributary of the Hoosac River.

A short distance above and below the bridge the brook flows through a gorge of white marble 30 to 60 feet deep and from 5 to 40 feet wide, the average width above the bridge being from 5 to 10 feet and below from 10 to 30 feet. The gorge is cut in a coarsely crystalline marble of Cambro-Ordovician age which belongs to the Stockbridge formation.

The top of the bridge is 44 feet above the water of the stream, the arch itself being about 8 feet thick in the middle. The span of the bridge is less than 10 feet long and the width, at present, is 25 feet. Hitchcock[19] states that when he studied the region (before 1839) there were two natural bridges, "though the upper [?] one is much broken." Only one bridge is in existence at present, but the second one, described by Hitchcock, appears to have been below, not above, the present one.

> "On examining the course of the stream and the rock in the vicinity of the North Adams Natural Bridge, one is struck with the width of the joints and the fact that the stream has for a portion of its course followed the joint planes."[20]

The bridge was formed as follows: When the stream flowed into the gorge through the ancient channel, it plunged over a fall into a preglacial valley. Some of the water in the joint plane nearest the present bridge seeped through an approximately horizontal crack a short distance under the present arch of the bridge. The solvent power of the water containing carbon dioxide (CO_2) gradually increased the size of the crack until it was still further enlarged by the erosion of the stream. The stream was finally entirely diverted from its former channel to its

[19] Edward Hitchcock: Geology of Massachusetts, vol. 1, 1841, pp. 287-288.

[20] H. F. Cleland: Formation of natural bridges, American Journal of Science, vol. xx, August, 1905, pp. 120, 121.

E. O. Hovey: Celebrated American caverns, pp. 14 and 206.

MARBLE NATURAL BRIDGE IN NORTH ADAMS, MASSACHUSETTS

present course. The gorge from the dam to the preglacial valley is a succession of broken pot-holes varying in size up to 6 or 8 feet in diameter, showing that after the tunnel was made the gorge was largely excavated in this way. The preglacial valley in which the Hudson Brook flows below the gorge is broad, but to some extent choked with glacial drift.

d. Illustrations of bridges formed by the widening of a joint.—By the widening of a joint near the source of a spring a portion of the country rock may be separated from the parent ledge so as to form a bridge. A good example of a bridge of this origin is the Natural Bridge at Chattanooga, Tennessee. The bridge (plate 24, figure 2) is a small one, being 8 or 10 feet in height, and spans a stream which has its source in a spring a few yards away. It is clearly formed by the widening of a joint, which thus separated the rock of which it is composed from the parent ledge. The bridge is used to some extent by foot passengers.

From Shepherd's[21] descriptions of two bridges in Green County, Missouri, it seems probable that they also are of this type, being formed by the widening of a joint or fissure near the mouth of a cavern.

One of these bridges is described as follows: This beautiful bridge (township 28 north, range 21 west, section 3, northeast ¼ of northeast ¼) abruptly heads a narrow gorge about 100 feet wide, which extends up from the bottom lands of the James River. The country road formerly passed over it. This bridge is 50 feet long, 15 feet wide, and 12 feet high.

Another bridge described is situated 4 miles east of Springfield, Missouri.

2. BY THE COMBINED ACTION OF SUBAERIAL AND SUBTERRANEAN EROSION

The following statement is one which, with a slightly modified phrasing, has done service in the geologies and geographies for a generation or two as an explanation of the origin of natural bridges:

"As a cavern enlarges and the surface of the land above it is lowered by weathering, the roof at last breaks down and the cave becomes an open ravine. A portion of the roof may remain, forming a 'natural bridge.'"[22]

The accompanying familiar diagram (figure 8) illustrates the theory. Theoretically one would expect to find a large number of bridges of this origin, but investigation has failed to bring to light any well-defined examples.

[21] E. M. Shepherd: Geology of Green County, Missouri, vol. xii, 1898, pp. 117-118.
[22] Norton: The elements of geology, 1905, p. 46.

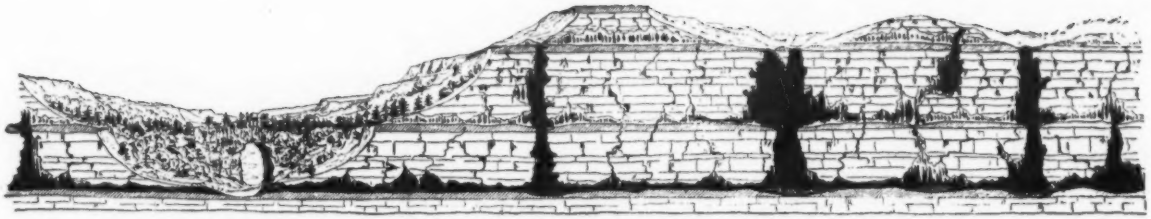

FIGURE 8.—*Diagram indicating Formation of Bridges from the "Remains of a great Cavern."*

Until recently no other explanation was considered in the geologies and geographies of North America. The diagram is reproduced from Shaler's "Aspects of the Earth"

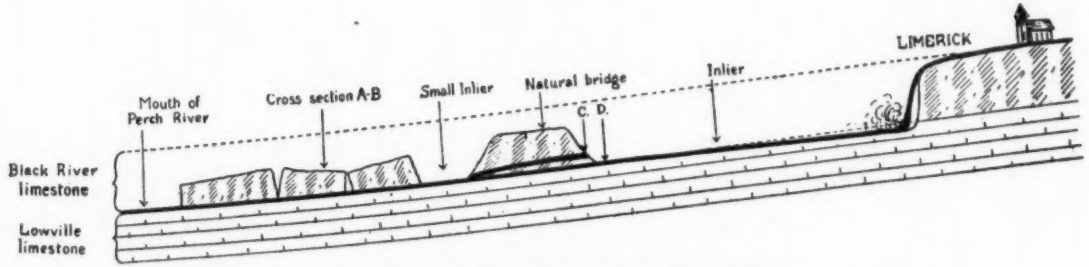

FIGURE 9.—*Section of Perch River Natural Bridge*

C, high-water subterranean course through the joints and cracks of the rocks; normal subterranean course on the surface of the Lowville limestone (after Ruedemann)

FIGURE 1.—NATURAL BRIDGE ACROSS ARCH CREEK, NEAR MIAMI, FLORIDA
Composed of oölitic limestone

FIGURE 2.—NATURAL BRIDGE FORMED BY GRAVITY, BIG HORN MOUNTAINS, WYOMING
Photograph by Walcott, U. S. Geological Survey

In a region of thick limestone, such as Edmonson County, Kentucky, where it is said there are 100,000 miles of underground caverns, one would expect natural bridges to be found in a later stage of physiographic development; for, as the surface of the land is lowered by subaerial erosion and the caverns are enlarged by subterranean erosion and solution, a time must, theoretically, come when all but small portions of the cave roofs will disappear, thus forming natural bridges. Caves formed in this way will differ in several particulars from those described under C 1. For example, as the land is lowered and the sink-holes are enlarged, the portion of the cavern roof left standing to form the bridge will be between wide basins which were originally sinks and which will clearly show their origin, since the valley will widen rapidly on either side of the bridge, thus showing their sink-hole origin. This consideration is well shown from a study of the topographic and geologic maps of limestone regions, particularly those of the Kingston, Tennessee, and Bristol, Virginia, folios of the U. S. Geological Survey.

3. *BY THE PARTIAL CAVING IN OF SUPERFICIAL TUNNELS*

Many bridges, initiated by solution, are formed by the partial caving in of the roof of a superficial tunnel, the tunnel being formed either (1) by the water of a stream which disappears in the joints of a limestone stratum and appears further down stream; or (2) by an underground stream emerging as a spring (the underground stream may have a single channel for but a short distance), the major portion of the roof of the tunnel collapsing and leaving one or more natural bridges.

a. Florida bridges.—There are a number of bridges of this origin in Florida. Large bridges occur on the Chipola River above Marianna; on the Saint Marks River south of Tallahassee, and on the Santa Fe River northeast of High Springs, the distance between the rise and sink of the latter stream being two or three miles. The natural bridge on the Chipola River, one-quarter to one-half mile wide, is submerged during high water, and a broad surface channel which crosses the one near High Springs is said to carry a portion of the flood water of the Santa Fe. The breadth of the surface channel near High Springs suggests that the natural bridge of the Santa Fe River may have been formed by the first method outlined in this paragraph. The bridge across the Chipola appears from the accounts to have a similar origin to the last.

A natural bridge across Arch Creek near Miami, composed of oolitic limestone (Pleistocene), more nearly satisfies our conception of a natural bridge than any other in Florida. In this case the arch (plate 26, figure 1) stands some 12 to 15 feet above the normal surface of the stream.

A small bridge of light gray marl is reported near Homosassa, Walton County, Florida, the width of the stream being about 20 feet and the width of the bridge, from the "sink" to the "rise" of the stream, being about one-third or one-fifth of a mile.[23]

b. New York bridges.—The New York natural bridges in Jefferson County are formed by the first method. The largest of these is one across Perch Creek (figure 9), but even this one does not fulfill the usual conception of a natural bridge, since the arch does not stand much above the surface of the stream at low water and is submerged at high water.

"The water flows underground in the Black River limestone, which is full of enlarged joints, and runs underground on the summit of the Lowville, which is less soluble. It eats out a channel in the basal portion of the Black River, and as this has no great thickness, it is not self-supporting over the arches, and much of the roof slowly slumps as the process goes on. It is here entirely a process of limestone solution and of slow slumping of the roofs due to non-support. The water goes down a widened joint athwart the stream course, and follows joint planes more or less parallel with the course, eating them away until they hold a larger and larger portion of the stream's capacity. There are several instances in the district where the entire flow is usually underground, but where the bare limestone surface of the channel shows clearly that the underground channel can not care for the entire volume during floods. Slight falling of the rocks is often influential in putting the streams back to the surface again."[24]

In one place the stream is brought to the surface, where it cuts across a preglacial channel at about right angles, emerging from under one wall of limestone and disappearing under the opposite wall.

c. Iowa bridges.—In the report on Jackson County, Iowa, Savage[25] describes a "series of natural bridges that have been developed by the waters of a small creek eroding a subterranean passage." "The upper or most northerly bridge has a length of 150 feet across the gorge and a width of about 60 feet." "[The stream] has carved a passage 50 feet in height beneath the span of the bridge." "About 8 rods farther down the stream a second arch crosses the ravine." The bridges are stated as being the result of the partial caving in of a cave roof.

d. Missouri Natural Bridge.—A natural bridge in Miller County, Missouri, differs from the other bridges which have been included in this

[23] Modified from descriptions given by Dr. E. H. Sellards in a letter to the writer and from the Second Annual Report of the Florida Geological Survey, 1909, pp. 36-37.

[24] H. P. Cushing in a letter to the writer, June 8, 1909. See also R. Ruedemann, "Types of inliers observed in New York." New York State Museum Bulletin no. 133, 1909, p. 175.

[25] T. E. Savage: Geology of Jackson County, Iowa, Geological Survey, vol. xvi, Annual Report, 1905, pp. 571-573.

division in that "a crevice or open joint penetrating the entire thickness of the roof has undoubtedly been one of the chief factors determining the tunnel." "Large slabs of rock have fallen from the under side of the bridge along the crevice." "The opening underneath the bridge is 200 feet long, 20 feet high, and 50 feet wide."[26]. It appears from the above that the bridge owes its origin to a longitudinal crack through which the water seeped, enlarging a tunnel beneath the surface.

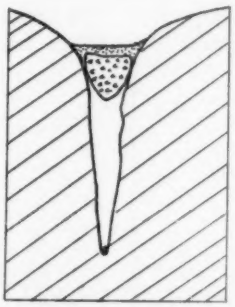

FIGURE 10.—*Diagram to show how a natural Bridge may be formed by Gravity*

A boulder fallen from the mountain side has lodged in a narrow ravine

e. Bridges in western Oklahoma.—Certain bridges in the Gypsum Hills of western Oklahoma may belong to this division. It is possible, however, that they should be included under C, 2. No descriptions of these bridges are available.

SUMMARY OF DIVISION C

It will be seen from the above that bridges initiated by solution are of three or four types: (1) Those formed by seepage along joints and bedding planes, thence emptying under a fall or rapid; (2) those formed in a region of thick limestone or gypsum by subaërial erosion, with the accompanying enlargement of the caverns and the sinks, and (3) by the local remains of comparatively superficial tunnels.

D. BRIDGES FORMED BY GRAVITY

1. *BY A STONE WEDGED IN A NARROW CHASM*

In mountainous regions, where erosion is rapid, the deep, narrow valleys which abound may be bridged over by a large mass of rock which is carried from the mountain side into the valley (figure 10). Several examples of this sort are discussed by Früh. Bridges of this type, in daily use by foot passengers, span the Tamina Valley, in Switzerland.[27] Such bridges are probably not uncommon in the narrow mountain gorges of this country; but as they are unusually small, it is difficult to learn of their location. The illustration (plate 26, figure 2) from the Big Horn Mountains shows a rather poor example from Wyoming.

[26] E. R. Buckley: Geology of Miller County, Missouri, Bureau of Geology and Mines, vol. 1, series 2, 1903, p. 13.

[27] J. Früh: Naturbrücken, p. 358; also Früh, Nachtrag zu Naturbrücken, 1907, Tafel 1, St. Gallien.

2. *BY A ROCK SEPARATED FROM ONE BANK AND LEANING AGAINST THE OPPOSITE BANK*

A bridge of unusual origin, and one which, as far as known, has no parallel in the United States, is illustrated by the accompanying section (figure 11). This bridge, which spans the gorge of the Emme, in Switzerland, is formed as follows: A rock of about 35 meters in height was

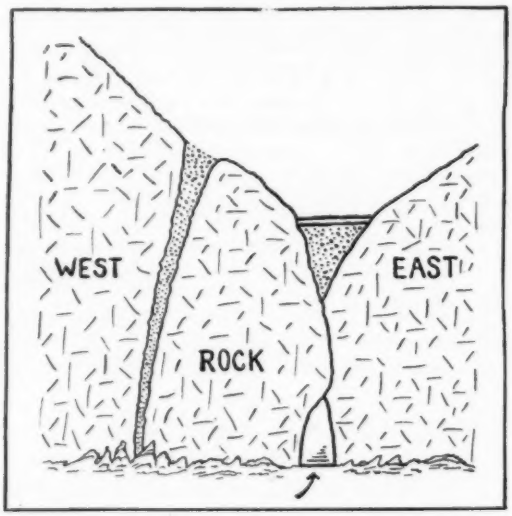

FIGURE 11.—*The "Rebloch" at Schangnau, in the Valley of the Emme, Switzerland*
Redrawn from Kaufmann

separated from the left bank of the gorge, and finally leaned against the wall of the right bank. The wedge-shaped crevice opening upward was then partly filled with debris, and became nicely leveled. The crevice on the left bank formed by the breaking away of the block is also more or less filled with debris.[28]

E. BRIDGES FORMED BY DEPOSITION

1. *BY DEPOSITION OF TRAVERTINE*

The only case of a valley of erosion spanned by a travertine deposit reported from North America occurs near the little Mormon village of Pine, about 90 miles south of Flagstaff, Arizona, and can be reached by a

[28] J. Früh: Ibid., p. 861.

FIGURE 1.—VIEW OF THE VALLEY OF PINE CREEK, ARIZONA

Showing the flat valley floor composed of travertine. The top of the bridge is at the far end (south) of the travertine floor. The springs which have supplied the lime are on the left. (See also plate 28, figures 1 and 2.)

FIGURE 2.—THE TRAVERTINE NATURAL BRIDGE, NEAR PINE, ARIZONA, FROM THE SOUTH

(See also plate 28, figures 1 and 2)

horseback journey of three days. Not only is the bridge unique in respect to its origin, but is, moreover, one of the most beautiful natural bridges in the United States, and, with the exception of those in San Juan County, Utah, one of the largest. As one journeys south from Flagstaff through the forest reserve he passes for miles over a lava plateau on which, with the exception of pine and cedar trees, there is little vegetation; when, then, the brilliant green of the irrigated, travertine-filled valley above the natural bridge comes into view, its beauty seems unusual (plate 27, figure 1). The vertical distance from the top of the bridge (plate 27, figure 2) to the creek bed is about 128 feet on the north and 150 feet on the south end. The opening beneath the bridge averages about 140 feet in width, and the length, at the narrowest place, approximately 400 feet. The thickness of the arch is approximately 75 feet, leaving the

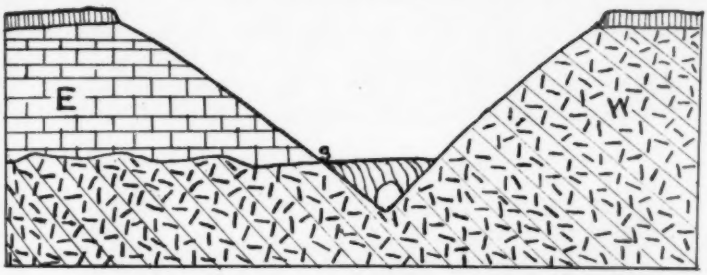

FIGURE 12.—*Diagrammatic Cross-section across Pine Creek, Arizona*

To show the geological relationships. The underlying rock is red porphyry, that immediately overlying is sandstone and limestone, and the capping rock is lava. (See also plates 27 and 28.)

height of the opening beneath the arch between 60 and 70 feet. The altitude of the bridge above the sealevel is approximately 4,700 feet. The origin of the bridge is as follows: Several large springs that flow into the valley from the east side contain lime in solution, which, upon evaporation or loss of carbon dioxide, is deposited as travertine (figure 12). For many years these springs have been depositing travertine in an old valley of erosion cut into red porphyry. As a result of this, an almost level floor of travertine of approximately the same height as the springs increased in width toward the west, filling the valley until it has forced the stream against the porphyry wall on the west side. In one place the travertine was strong enough to support itself, until it was built over the stream to the opposite side of the valley, thus forming a natural bridge. As will be seen from the illustration (plate 28, figure 2), the rock of which the bridge is composed is stalactitic in structure and quite compact. Be-

neath the arch (plate 28, figure 1) of the bridge are several caves of considerable extent, from the roof of which hang stalactites and from the floor of which stalagmites arise. These caves are reached from below by ladders which have been erected by Mr. Goodfellow, the owner of the bridge.

The extent of the terrace above, and including the bridge, is about 25 acres, and is covered with a good soil which is irrigated from the springs and produces abundant crops of fruit and alfalfa. A small portion of the north end of the cultivated tract is apparently not underlaid with travertine, but is formed by sediment carried in by a small stream. This may, however, also be underlaid by travertine. Travertine terraces, such as that of the natural bridge, also occur in Fossil Creek and Beaver Dam Creek, on the road between Pine and Camp Verde and Flagstaff. No natural bridge, however, has been built in either of these valleys.

The natural bridge of Papigno,[29] east of Terne, is, according to Keller, of this origin. Another bridge near Hierapolis, in Asiatic Turkey; another at Mesquitin, between Tunis and Constantine, in Africa, but which is now said to have fallen, are said to be of this origin.[30] Two travertine bridges are also reported from Chile which span a gorge of the Rio Maipo.

2. *BY SNOW AND AVALANCHES*

Snow and avalanche bridges should be mentioned here, since they are strictly natural bridges.

Conclusions

It will be seen from an analysis of the above—

(1) That natural bridges occur in glaciated as well as unglaciated regions, and that the former, at least, have required a short time, geologically speaking, for their formation.

(2) That they must necessarily be short-lived structures, the life depending upon several factors—the character and composition of the rock, the climatic conditions, etcetera. The North Adams bridge, for example, is a postglacial structure which was evidently formed during the later half of postglacial time, judging from the width of the gorge above and below the bridge.

(3) That they are formed of various materials—limestone, sandstone, marble, gypsum, conglomerate, marl, clay, shale, schist, and lava.

(4) That they fall into at least five well marked divisions, some of which have several subdivisions.

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[29] Pet. Mitt., 1881, pp. 329-330, quoted by Früh, p. 362.
[30] Güssfelt, as quoted by Früh. Ibid., p. 363.

FIGURE 1.—SIZE AND CHARACTER OF THE OPENING UNDER THE ARCH OF THE NATURAL BRIDGE NEAR PINE, ARIZONA

The ladders lead to a cave which is situated near the arch of the bridge. Height, about 75 feet to underside of arch

FIGURE 2.—CHARACTER OF THE TRAVERTINE OF THE NATURAL BRIDGE NEAR PINE, ARIZONA

(See also plate 27, figure 2)

(5) That it is unsafe to make a definite statement as to the origin of a natural bridge, even when the rock and topography are known, without a careful study in the field.

(6) As concerns the stage of erosion, it may be said in general that they may occur in all stages from youth to advanced maturity or early old age.

If natural bridges were to be classified according to the stage of erosion, it would be found that (*a*) those formed by gravity and by deposition are likely to be found in early stages of valley erosion; (*b*) those initiated by solution, as in C 1, are more likely to occur in the youthful portion of a valley, or, as in C 2, in an advanced stage of the erosion of a region; (*c*) those formed by the perforation of the neck of an incised meander are likely to occur in a submature stage of valley development, either in a new cycle following an advanced stage of a previous cycle or in a more resistant stratum upon which the stream meandered temporarily; (*d*) those formed by pot-hole action may occur in any stage between youth and advanced maturity, and that (*e*) sea erosion bridges are more likely to occur only in rather early energetic stages of sea erosion.

Catalog of North American Natural Bridges

The following is a catalog of North American natural bridges, their location, and the character of rock of which they are composed:

Alabama.—A bridge composed of conglomerate (millstone grit) is reported from Marion County.

Arizona.—(1) The travertine bridge near Pine.
(2) Bridge formed of a petrified log near Adamana.
(3) A bridge near the New Mexico line reported by J. Gardiner, Jr.[31]

Canada.—The limestone bridge across the Kicking Horse River near Field, British Columbia.

California.—(1) The Santa Cruz wave-cut bridge composed of shale.
(2) A bridge across Volcano Creek, a tributary of the Kern in the Sierras.

Florida.—A number of bridges occur in the limestone of this State, of which four are described in this paper.

Indiana.—A sandstone (?) bridge near Attica.

Iowa.—Limestone bridges in Jackson County.

Kansas.—Two gypsum bridges are described in volume v, 1899, page 73, plates 26, 27, of the Kansas Geological Survey. The best of these

[31] Science, vol. 6, 1885, p. 67.

spans Bear Creek, south of Sun City, the height of which is 47 feet in the highest place and the width of the span 35 feet. The origin is not clear from the description.

Kentucky.—Sandstone bridges in Powell and Wolfe counties.

Massachusetts.—The North Adams marble bridge.

Missouri.—Limestone bridges in Miller and Green counties.

New York.—Bridges in Jefferson County composed of Black River limestone.

Oklahoma.—"Natural arch" of limestone, 15 miles southeast of McAlester. Bridges in the Gypsum Hills, in western Oklahoma.

South Dakota.—(1) The sandstone bridge near Buffalo Gap.
(2) A clay bridge spanning Porcupine Creek.
(3) The Big Bad Lands sandstone bridge.

Tennessee.—The sandstone bridge on Lookout Mountain.

Utah.—The four great sandstone bridges of San Juan County.

Virginia.—The great limestone bridge across Cedar Creek.

Vermont.—The schist bridge across the Lamoille River and one other.

Wyoming.—(1) The sandstone bridge spanning Le Perle Creek, in Converse County.
(2) The lava bridge in Yellowstone National Park.
(3) A bridge across Rio Piedra, Wyoming (?).

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ALASKAN EARTHQUAKES OF 1899[1]

BY LAWRENCE MARTIN

(Presented in abstract before the Society December 29, 1909)

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[1] The field observations upon which this paper is partly based were made in the summer of 1905, in connection with a general geological study of the Yakutat Bay region by a U. S. Geological Survey party under the direction of Prof. R. S. Tarr. A grant of money, obtained through the assistance of the American Geographical Society of New York, made it possible for the author to accompany this party as special assistant in physiography and glacial geology.

The office work upon which this paper is more largely based was done during the winters of 1906-8, at the University of Wisconsin, in connection with the preparation of a U. S. Geological Survey professional paper by R. S. Tarr and the author, dealing with these earthquakes and now in preparation.

Acknowledgment is made to H. P. Ritter and R. D. Oldham for the loan of manuscript notes, to H. F. Reid and the U. S. Coast and Geodetic Survey for newspaper clippings, to many seismologists for data, to many persons in Alaska and Canada for replies to earthquake circulars, and to R. S. Tarr and G. K. Gilbert for suggestions regarding the subject-matter of this paper.

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INTRODUCTORY

THE EARTHQUAKES AND THEIR RESULTS

The severe earthquakes in the Yakutat Bay region, Alaska, in September, 1899, were accompanied by faulting, tilting and warping, by changes of level along the coast, and by glacial oscillations, some of which are still in progress. These have already been described.[2] The earthquakes themselves, however, were only briefly referred to in the reports published. It is the purpose of the present paper to describe these earthquakes.

They lasted 27 days—September 3 to 29, 1899—and included four or five world-shaking disturbances and hundreds of minor shocks. During four weeks there was almost constant palpitation of this part of the earth's crust. The shocks were most severe on September 3, 10, and 23, and were great on the 15th, 17th, 26th, and 29th (figure 6). On the 10th there were over 50 small shocks and two world-shaking disturbances. The greatest faulting took place on September 10, not September 12, as Dr. G. K. Gilbert[3] inferred from an erroneous newspaper report, and probably not September 15, as stated by Comte F. de Montessus de Ballore.[4]

Seismographs and magnetographs in Canada, Mexico, British Isles, Belgium, France, Netherlands, Spain, Germany, Italy, Austria, Russia,

[2] R. S. Tarr and Lawrence Martin: Recent change of level in Alaska. Science, N. S., vol. xxii, 1905, pp. 879-880; Bull. Geol. Soc. Am., vol. 17, 1906, pp. 29-64; Geographical Journal, vol. xxviii, 1906, pp. 30-42.

R. S. Tarr: Recent advance of glaciers in the Yakutat Bay region, Alaska. Bull. Geol. Soc. Am., vol. 18, 1907, pp. 257-286.

Lawrence Martin: Possible oblique minor faulting in Alaska. Economic Geology, vol. ii, 1907, pp. 576-579.

[3] Harriman Alaska Expedition, vol. iii, 1903, p. 23.

[4] La Science Seismologique, Paris, 1907, pp. 31 and 415.

Argentina, India, Japan, Java, Mauritius, and South Africa (figure 6) recorded these shocks, several of which equalled, and one (September 10) far surpassed, the 1906 California earthquake in duration and amplitude. In this wilderness portion of Alaska there was no serious property damage and no recorded loss of life.

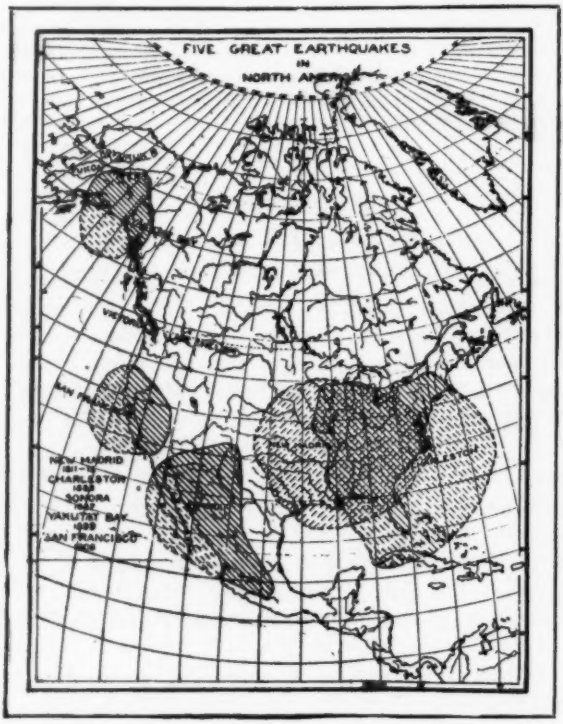

FIGURE 1.—*Areas shaken by five great Earthquakes in North America*

Several earthquakes in Jamaica, Mexico, and New England not shown. Maximum areas of New Madrid, Sonora, and Yakutat Bay earthquakes probably much greater, but extreme observations of weak shocks not obtainable in wilderness areas surrounding these three epicentra, as was done for Charleston and California. Minimum area of Yakutat Bay shock of September 10, 1899, shown.

The phenomena accompanying the shocks were observed at distances of 5 to 730 miles, and perhaps raised water waves on Lake Chelan, in Washington, over 1,200 miles away. The minimum land area shaken was 216,300 square miles (figure 1), the land and water area being

400,000 to 500,000 square miles, while distant observations suggest that the shocks may have been sensible over 1,539,000 square miles. The reliable time records, aside from seismograms, are meager but decisive. The shocks were tectonic and attendant upon renewed earth movement accompanying mountain growth.

LOCATION OF AREA

These earthquakes seem to have originated in or near Yakutat Bay, which lies close to the bend of the Saint Elias-Chugach coast range, near

FIGURE 2.—*Map of Alaska (after Brooks)*
Showing relation of mountain axes to earthquake origin in Yakutat Bay

latitude 140 degrees west and longitude 60 degrees north. Figure 2 shows the general location of the Yakutat Bay region as well as the mountain axes in Alaska to which these shocks are related. The Chugach Mountains average 6,000 to 7,000 feet in height, the Saint Elias Range 10,000 to 19,000 feet.

Among the Alaskan towns existing in 1899 Skagway lies 150 miles east of Yakutat Bay, Juneau and Sitka between 200 and 250 miles southeast, and Valdez 250 miles northwest. Glacier Bay is 150 miles east of Yakutat Bay. The Wrangell Mountains, including Mount Wrangell and other active volcanoes, extend parellel to the Saint Elias Range and

northwest of it, and from them the Copper River flows southward, crossing the Chugach Mountains and entering the Pacific about 200 miles west of Yakutat Bay. The Alsek River flows southward from the interior of Alaska, entering the Pacific about 60 miles east of Yakutat Bay. The White River and the Tanana, headwaters of the Yukon from the Saint Elias and Wrangell Mountains, flow northward.

TOPOGRAPHY AND GEOLOGY OF THE EARTHQUAKE ORIGIN[5]

The three topographic features near Yakutat, around which was the earthquake origin, are: (1) the Yakutat foreland, a glacial coastal plain less than 250 feet above sealevel; (2) the foothills, rising from 3,000 to 4,550 feet, and (3) the Saint Elias Range, 10,000 to 19,000 feet high. Yakutat Bay, a fiord shaped like a bent arm, consists (figure 3) of (*a*) a broad outer bay in the foreland; (*b*) Disenchantment Bay, a deep fiord in the foothills and mountains, and (*c*) Russell Fiord, partly in the mountains, partly in the foothills, and partly in the foreland. A piedmont ice-sheet, the Malaspina glacier, covers the foreland on the west side of Yakutat Bay, and there are extensive alpine glaciers entering the fiords and mountain valleys and supplied from the snowfields, which cover everything above 3,000 feet where slopes permit. The fiords are chiefly the work of glacial erosion.

The geology of this area of the earthquake origin includes rocks of at least four different ages: (1) Paleozoic or older intrusive and metamorphic rocks; (2) the Yakutat group of sediments, perhaps Mesozoic; (3) the Tertiary coal-bearing group, and (4) the Quaternary glacial and terrestrial accumulations. The Quaternary formations cover the Yakutat foreland and form valley deposits in the mountains. The Tertiary includes an exceedingly small area at the base of the foothills west of Yakutat Bay. The Yakutat group includes all the foothill region and part of the mountains. A northwest to southeast line extending through the northwest arm of Russell Fiord (figure 3) separates the Yakutat group from the metamorphic and igneous older group of rocks. This is an old fault-line, one of those along which renewed movement caused the 1899 earthquakes, particularly that of September 10. The prospectors who experienced these earthquakes from a camp near the junction of Disenchantment Bay and Russell Fiord (figure 3) were, therefore, right on a fault-line. Another old fault separates the Tertiary coal-bearing group from the Yakutat group. A third old fault, inferred by I. C. Russell in 1890, on the basis of topographic form,[6] separates the

[5] Fully described in U. S. Geological Survey Professional Paper no. 64, 1909.
[6] National Geographic Magazine, vol. 3, 1891, p. 57.

Yakutat foreland from the foothills. Along each of these three older faults and several others, there was renewed movement during the 1899 earthquakes.

OBSERVERS OF THE EARTHQUAKES

The observers of the earthquakes include eight prospectors who were at the junction of Disenchantment Bay and Russell Fiord, tributaries to Yakutat Bay, during the most severe shocks; a few whites at Yakutat village, at the entrance of the bay; natives at Yakutat and at Dry Bay, near the mouth of Alsek River, to the east; the captain of a vessel at Yakataga, 100 miles to the west; prospectors at Controller Bay; a Coast and Geodetic Survey party at Cape Whitshed, at the mouth of Copper River; army officers in the Chugach and Wrangell Mountains; cannery employees in Glacier Bay; telegraph operators along the Klondike trail; people living at Skagway, Juneau, Sitka, Valdez, etcetera, and prospectors, missionaries, United States and Canadian government officials, and others in various parts of the 216,000 square miles of wilderness within which the shocks are known to have been felt.

These persons have been corresponded with through a series of 600 earthquake circulars, which were sent in 1907-1908 to the region disturbed, and their observations have been carefully studied.

OBSERVATIONS BY GEOLOGISTS

The only geologists who are known to have observed these earthquakes are Mr. Oscar Rohn, the geologist accompanying Captain Abercrombie's U. S. Army Expedition, who was in the Wrangell Mountains, 170 miles northwest of Yakutat Bay; Mr. A. H. Brooks, of the U. S. Geological Survey, who was near the Tanana River, 250 miles northwest of Yakutat Bay; Prof. J. C. Gwillem, of the Geological Survey of Canada, who was near Atlin Lake, 215 miles southeast of Yakutat Bay, and Mr. F. C. Schrader, of the U. S. Geological Survey, who was on the Koyukuk River, 670 miles northwest of Yakutat Bay. The Harriman Expedition had left Yakutat Bay on the return trip about three weeks before the earthquakes.

CONTEMPORARY DESCRIPTIONS

Descriptions of these earthquakes first appeared in the newspapers. Over fifty such accounts have come to the writer's attention, including items in daily and weekly papers in Alaska, in the United States and Canada, and in Europe. Magazines also referred to the earthquakes briefly; for example, the National Geographic Magazine,[7] the Scientific

[7] Vol. 10, October, 1899, p. 421.

American,[8] and Current Literature.[9] The Governor of Alaska, the Commissioner of Education, the commanders of vessels, United States Army officers, Coast Survey engineers, Weather Bureau observers, postmasters, many Canadian officials, as well as numerous prospectors, missionaries, and others, made notes concerning these earthquakes and referred to them briefly in their reports.

STUDY BY SEISMOLOGISTS

The delicate tremors which traversed the rocks of the earth's crust were recorded by seismographs in practically every observatory in the world where such instruments were then installed. Many magnetographs also recorded them. Several seismologists have given special attention to the records made by this group of earthquakes and specific mention will be made later of the studies by Prof. John Milne, Dr. F. Omori, Dr. R. D. Oldham, several Italian seismologists, and others who knew of the location, time of origin, etcetera, of these earthquakes long before the faulting, the 47-foot uplift, and the glacial oscillations which accompanied or resulted from these shocks were known.

PLAN OF PRESENTATION

The observations in Alaska will be described first of all, the shocks of September 3, those of September 10, and those of September 11 to 29 being presented in order. The seismograph records will then be described, the time records discussed, the disturbed area shown, and the earthquake series will be briefly compared with other great seismic disturbances in Alaska, North America, and the world in general. In conclusion, the relationships of these earthquakes to life will be brought out.

Observations in Alaska

EARTHQUAKE OF SEPTEMBER 3, 1899

List of localities.—The first shock in this series (unless possibly the avalanches heard near the headwaters of the White and Tanana rivers at 8 p. m. on August 27, 1899, were due to an earlier shock on the north side of the mountains[10]) occurred on September 3, at 3h. 3m. 28s., mean local time at Yakutat (or September 4, at 0h. 21m. 40s., Greenwich mean time). The fact that September 3 was the first Sunday in Sep-

[8] Vol. lxxxi, December 23, 1899, pp. 405-406.

[9] Vol. xxvii, February, 1900, p. 123.

[10] Journal of A. H. Brooks for 1899; Seattle Post-Intelligencer, September 23, 1899; Victoria Semi-Weekly Colonist, September 25, 1899; Seattle Weekly Times, October 4, 1899.

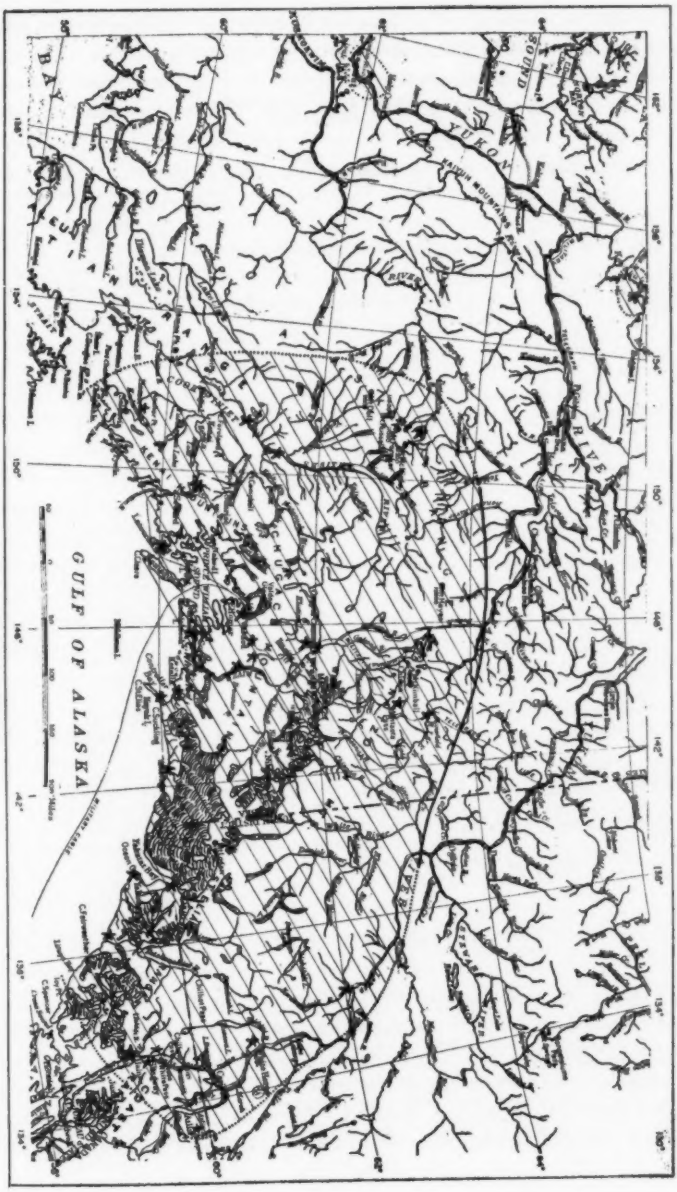

FIGURE 3.—*Map of Part of Alaska*

Showing minimum area within which Yakutat Bay earthquake of September 3, 1899, was felt. Detached areas of shocks on Koyukuk and Yukon rivers. Stars at places of known observations.

tember has simplified collecting the record. It is known to have been felt at the following places (figure 3):

Places.	Location with respect to Yakutat Bay.	Observers.
Disenchantment Bay....	In Yakutat Bay.....	J. Bullman, L. A. Cox, S. Cox, A. Flenner, J. D. Fults, Jr., A. Johnson, T. Smith, and D. Stevens.
Yakutat Village....	Mouth of Yakutat Bay...	C. E. Hill, R. W. Beasley, Mrs. Esther Early, Albin Johnson, and others.
Dry Bay Village	60 miles east of Yakutat...	Dry Bay natives.
Dyea.....	150 miles east-southeast...	A. J. Walker, J. R. Beegle, and others.
Haines Mission	160 miles east-southeast...	Prospectors.
Skagway	160 miles east southeast..	F. S. Williams and others.
Whitehorse.....	170 miles northeast.....	G. S. Fleming.
Tantalus	190 miles northeast.....	Northwest mounted police.
Surprise Lake.....	240 miles east.....	John Bimms.
Pacific Ocean	West of Yakutat.....	
Yakataga.....	100 miles west of Yakutat.	B. Durkey, S. E. Dover-spike.
Katalla.....	170 miles west	C. W. Chamberlin.
Cape Whitshed	220 miles west-northwest	H. P. Ritter, E. B. Latham, and others.
Chugach Mountains.....	210 miles northwest.....	W. R. Abercrombie.
	240 miles northwest.....	W. C. Babcock.
	240 miles northwest.....	E. S. Larson.
Valdez	250 miles west-northwest.	L. S. Camicia.
Copper River.....	250 miles northwest.....	J. F. Rice.
	250 miles northwest.....	A. N. Powell.
Wrangell Mountains	170 miles northwest by north.	Oscar Rohn.
Nutzotin Mountains.....	250 miles north-northwest.	G. B. Rorer.
Tanana River.....	250 miles north-northwest.	A. H. Brooks, W. J. Peters, and others.
Latouche.....	295 miles west	E. F. Glenn.
Kenai Lake.....	380 miles west	W. E. Lennox.
Homer.....	430 miles west	George Jammé.
Susitna River.....	390 miles west-northwest.	F. R. Falconer.
Tyonek	410 miles west-northwest.	Prospector.
Alaska Range.....	480 miles northwest	J. S. Herron.
Koyukuk River.....	730 miles west-northwest.	F. C. Schrader, T. G. Gerdine, D. C. Witherspoon, and others.
Lower Yukon River.....	730 miles west-northwest.	Rev. N. N. Amcan.

Disenchantment Bay.—The Disenchantment Bay point of observation is within 5 miles of the origin of the great earthquake of September 10, and perhaps the September 3d shock also originated here. Eight prospectors, who were washing the gravels of an alluvial fan between the Hubbard and Variegated glaciers (figure 5) for gold and platinum, experienced the earthquake. They were J. Bullman, L. A. Cox, S. Cox, A.

Flenner, J. P. Fults, Jr., A. Johnson, T. Smith, and D. Stevens. Messrs. Cox and Fults have written newspaper accounts of their experience[11] and Mr. Flenner has described it to the writer. This shock was not severe enough in Disenchantment Bay to throw a man off his feet. This is within the area of indurated rocks.

Yakutat.—At Yakutat village, thirty miles distant, Mr. C. E. Hill, a surveyor; Mr. Beasley, the storekeeper; Rev. Albin Johnson, the missionary, and Mrs. Early, a native woman, have stated[12] that the houses rocked and shook violently, a door swung to and fro and shut with a crash, dishes rattled, a table moved, the trees and flag poles rocked back and forth, and the water crossing a reef in the bay was whipped into a mass of seething foam. It was impossible to stand up without support. The region is one of unconsolidated glacial deposits.

There was a general shivering of the earth and then a long jerk; the vibrations were from two to three seconds in length, coming from the northwest and running southeast, slowly at first and then coming shorter and faster and irregularly until they had lasted about 5 minutes. There were slight tremors the rest of the day.

Dry Bay.—At the native settlement at Dry Bay, near the mouth of Alsek River, 60 miles east of Yakutat, the shock was so severe that men were unable to stand.

Lynn Canal.—At Dyea, 150 miles east of Yakutat, A. J. Walker and J. R. Beegle, of the United States customs service, report that the shocks were severe enough to cause lamps to swing, doors and windows to rattle, water to spill from dishes, and piles of freight on wharves to be overturned. Earth-waves traversed the sand flat on which Dyea stands, making people dizzy and causing difficulty in walking.

At Haines Mission, south of Dyea, the shocks were accompanied by the moving of furniture, the swaying of trees, rolling of logs, difficulty in walking, and by cracking of the ground.[13]

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[11] L. A. Cox: Sitka Alaskan, October 14, 1899.

J. P. Fults, Jr.: The Seattle Daily Times, September 28, 1899; New York Sun, September 29, 1899.

[12] C. E. Hill: Seattle Post-Intelligencer, September 23, 1899; San Francisco Examiner, clipping dated Seattle, September 21, 1899; Toronto World, September 25, 1899.

The statements from Mr. Beasley, Rev. Mr. Johnson, and Mrs. Early are from replies to the earthquake circulars and, in the case of Mr. Beasley, from conversations with the writer. In succeeding pages much information regarding earthquake observations in Alaska is quoted. In cases where newspaper articles, official reports, diaries, etcetera, are not cited the information was obtained from the earthquake circulars sent out or from interviews with the observer. Exact quotations or abstracts have been made in most cases, although the quotation-marks have not usually been inserted in this text.

[13] San Francisco Chronicle, September 22, 1899; same, dispatch dated Tacoma, September 9, 1899.

At Skagway, 160 miles east of Yakutat, the shock of September 3 caused buildings and telephone poles to rock from north to south for 3¾ minutes,[14] at 3.17 p. m. Pools of water sloshed about in the streets and beer splashed out of vats in the brewery. The shock lasted long enough for F. S. Williams, the deputy collector of customs, to run from the second floor to the street and wait for the shocks to end. It made people stumble while walking and cracked the putty around large plate-glass windows. A small water-wave was reported in Lynn Canal.

Klondike Trail.—At Whitehorse, 170 miles northeast of Yakutat, in Yukon Territory, Mr. G. S. Fleming, the government telegrapher, felt a slight shock at 3 p. m., lasting 30 or 40 seconds. His dog crouched in terror at the beginning of the tremor and ran home whining.

At Tantalus (Carmacks), a station of the Royal Northwest Mounted Police, 190 miles northeast of Yakutat, the post diary records that a slight shock of earthquake was felt during the afternoon.

At many other points on the trail to the Klondike district this shock was also observed.[15]

Canadian Coast Range.—In the Surprise Lake district, about 240 miles east of Yakutat, John Bimms experienced violent earth tremblings on September 3.[16] Dust from distant mountains suggested smoking volcanoes, but may have been due to avalanches. After-shocks occurred occasionally until September 7.

Pacific Ocean west of Yakutat.—Three different vessels report severe storms or other exceptional conditions at sea west of Yakutat, near Kodiak, etcetera, on September 3. The newspapers suggest a connection between the earthquake and the storms.[17] There seems no good reason for such association, as no evidences of the earthquakes were observed on these vessels.

Yakataga and Controller Bay.—At Yakataga, 100 miles west of Yakutat, S. E. Doverspike, a prospector, states that treetops snapped and earth-waves were felt, the ocean beach was raised three feet, and there were 48 shocks during the ensuing six hours. Captain Durkee, of the schooner *Bellingham*, which was anchored off Yakataga, says the first shock was heavy and continued by shocks every ten to fifteen minutes; avalanches were seen; a current ran offshore at the rate of 3 or 4 miles

[14] San Francisco Chronicle, September 10, 1899; Seattle Weekly Times, September 27, 1899; New York Tribune, September 12, 1899; Chicago Tribune, September 12, 1899.

[15] New York Daily Tribune, September 12, 1899; Chicago Daily Tribune, September 12, 1899.

[16] San Francisco Chronicle, October 5, 1899.

[17] New York Evening Post, September 26, 1899; Seattle Weekly Times, October 4, 1899.

an hour, and the tide only rose subsequently to half the height indicated by the tide tables, evidently because of the same uplift of the shoreline observed by Mr. Doverspike. There was a roar and the schooner trembled.

At Kayak Island and Katalla, on Controller Bay, 170 miles west of Yakutat, the shocks were also felt and there were great avalanches[18] and dust clouds.

Cape Whitshed.—At the Coast and Geodetic Survey camp west of the Copper River delta, 220 miles west of Yakutat, the shocks observed by H. P. Ritter and E. B. Latham came at 2.40 p. m.[19] These Cape Whitshed observations, at a point whose exact location is known (longitude 145° 54′ 35″ west, latitude 60° 27′ 34″ north) and timed with a good and well-rated chronometer, constitute the most valuable local records of these earthquakes. At only two other points within the shaken area are the time records capable of correction to the standard Greenwich mean time and comparable with the precise times of the seismograph records.

The shock lasted two minutes and was a violent earthquake—direction northeast and southwest—turning floating bottles toward the northeast and throwing the water in a shallow creek out on the bank. The weather was clear, pleasant, and warm. All the movements were apparently lateral and eight or more after-shocks were felt. One at 3h. 22m. 30s. had a few seconds' duration. The time of two light shocks during the afternoon was not noted. A shock at 6h. 45m. lasted ten seconds. Two quite severe shocks came at 7h. 10m., lasting five seconds. Two moderate shocks occurred at 7h. 44m., having a duration of ten seconds, and there were several light ones after this before the Coast Survey observers fell asleep.

Chugach Mountains.—On the Tsina River, 210 miles northwest of Yakutat, at about 2 p. m., Capt. W. R. Abercrombie, of the U. S. Army, felt a succession of shocks which tripped him while walking, caused groves of cottonwoods to wave like wheat, started heavy landslides, and damaged glaciers.

In another part of the Chugach Mountains, 240 miles northwest of Yakutat, Lieut. W. C. Babcock noted the commencement of the earthquakes at 2.28 p. m.[20] The shock began gently, gradually increased in violence until it was impossible to stand erect, and then gradually de-

[18] Dr. C. W. Chamberlin, Seattle Daily Times, September 21, 1899; San Francisco Examiner, dispatch dated Juneau, September 14, 1899.

[19] Annual report of H. S. Pritchett, Superintendent U. S. Coast and Geodetic Survey, Washington, 1901, pp. 78 and 206, and manuscript notes furnished the writer.

[20] Copper River Exploring Expedition. Senate Document 306, 56th Congress, 1st session, 1900, pp. 73-74; Senate Report 1023, 56th Congress, 1st session, 1900, p. 276; extracts from Lieutenant Babcock's diary.

creased; it lasted 1 minute and 10 seconds. The north-south vibrations were so violent that Lieutenant Babcock saw the ground move, cook pails were upset, tall spruces swayed dangerously, and he had a feeling not of fear, but of utter helplessness, accompanied by a slight nausea resembling seasickness. After the shaking eight muffled reports at intervals of about 12 seconds were heard, perhaps from falling avalanches.

In the Tiekel Valley, near Copper River, E. S. Larson says the shocks caused the ground to move, the trees to wave, and woke a man sleeping on the ground. The date was not recorded, but possibly is that of September 3.

At Valdez, 250 miles northwest of Yakutat Bay, Dr. L. S. Camicia, a watch-repairer and optician, reports a strong shock at 2.33 p. m., during which it was impossible to stand on one's feet. Jacob Suter[21] says his chair creaked and swayed, the log cabin shook, and trees rocked. Valdez was not damaged by water waves because the shock came at low tide.

Upper Copper River.—At Copper Center, 250 miles northwest of Yakutat Bay, Mr. J. F. Rice, a quartermaster's clerk of the Copper River Exploring Expedition, was shaken off a stump on which he was standing and making observations at 2 p. m.[22] The ground rocked, trees swayed as in a hurricane, and avalanche roars were heard.

Mr. A. N. Powell, a scout and guide for the same expedition, who was near the junction of the Klutina and Copper rivers, said the earth gave about three swings during 5 seconds, and that there was nothing unusual in the smoking of Mount Wrangell at the time.[23]

Wrangell Mountains.—Mr. Oscar Rohn, geologist for the Copper River Exploring Expedition, was near the divide of the Nizina and Chisana (Tanana) glaciers, in the Wrangell Mountains. This is 170 miles northwest of Yakutat. The surface of the glacier swayed up and down with a slow undulating movement, violent and persistent enough to cause a touch of nausea. The vibrations were perhaps two or three a minute and the motion approximately northeast and southwest. There were minor rapid after-shocks.[24]

Nutzotin Mountains.—Near Mentasta Pass shocks, presumed to be of this group, were felt by Mr. G. B. Rorer, a prospector. This pass across the Nutzotin Mountains is about 250 miles northwest of Yakutat.

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[21] Seattle Daily Times, September 21, 1899; same, September 29, 1899.

[22] Senate Document 306, 56th Congress, 1st session, Washington, 1900, p. 102; and Senate Report 1023, 56th Congress, 1st session, Washington, 1900, p. 788.

[23] Op. cit., page 132 in Document 306 and page 804 in Report 1023.

[24] Copper River Exploring Expedition. Senate Document 306, 56th Congress, 1st session, Washington, 1900, p. 123; and Senate Report 1023, 56th Congress, 1st session, Washington, 1900, p. 800.

Tanana River.—Messrs. A. H. Brooks, W. J. Peters, and a U. S. Geological Survey party were just north of the Tanana River, near latitude 143 degrees west and longitude 63 degrees north, a little over 250 miles northwest of Yakutat. At 3.30 in the afternoon they heard a series of loud, distant sounds, resembling the sound of blasting or the discharge of heavy artillery, repeated at irregular intervals with varying intensity for five or ten minutes, then seeming gradually to lose their intensity and die away. Similar sounds were heard for about a minute at 8 p. m.[25]

Kenai Mountains.—At Latouche, on the west side of Prince William Sound, 295 miles west of Yakutat, Lieut. E. F. Glenn, of the U. S. Army, reports having his attention attracted to this earthquake by feeling as if he were about to fall.[26]

Near Kenai Lake, 380 miles west of Yakutat, a shock observed by Mr. W. E. Lennox on an unrecorded date in the fall of 1899, perhaps September 3, caused lamps to swing, goods to roll from the shelves of a store, and the ground to sway sufficiently to cause dizziness.

At Homer, Kachemak Bay, 430 miles west of Yakutat, Mr. George Jammé, a mining engineer, felt this September 3d earthquake, which threw him against a drawing table.

Cook Inlet.—At Susitna Station, near the head of Cook Inlet and 390 miles west of Yakutat, the September 3d earthquake was observed by Rev. F. R. Falconer at 2 p. m. The shock seemed gentle, with a wave-like motion.

At Tyonek, on the west coast of Cook Inlet, a severe shock was reported to A. H. Brooks by a prospector, whether on the 3d or 10th of September not being recorded.

Alaska Range.—Northwest of Mount McKinley, in the Alaska Range and 480 miles northwest of Yakutat, near the headwaters of the Kuskokwim River, in latitude 63° 30′ north, longitude 152° 30′ west, Lieut. J. S. Herron, of the U. S. Army, felt the September 3d earthquake at 2 p. m.[27] Another shock was felt at 2.30 p. m. The first shock was very severe and seemed to be right under Lieutenant Herron, lasting five seconds. It shook the ground, caused waves two feet high on a creek, made it difficult to stand without holding on to a tree, and impossible to walk. It was a severe and continual rocking or shaking of the earth and not a gradual movement.

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[25] From the journal of A. H. Brooks, September 3, 1899.

[26] Explorations in and about Cooks Inlet. Senate Report 1023, 56th Congress, 1st session, Washington, 1900, p. 715.

[27] Explorations in Alaska, 1899, War Department, Adjutant General's Office, No. xxxi, Washington, 1901, p. 38; Lieutenant Herron's diary for 1899.

Koyukuk River.—Near latitude 66° north and longitude 156° 15′ west, in the Koyukuk River, a northern tributary of the Yukon, is Treat Island, 670 miles northwest of Yakutat (figure 3). Near here Messrs. F. C. Schrader, T. G. Gerdine, D. C. Witherspoon, and a U. S. Geological Survey party encountered water waves at 2.22 p. m., September 3, in a stretch of river otherwise as calm as a mill-pond. Two of these waves were 1½ to 2 feet high in midstream and rose a foot or more above normal river level upon the banks. They moved rapidly upstream, north-northwest, washing back several hundred yards on very flat shores and leaving pools and patches of water, foam, froth, sticks, and vegetable rubbish. Mr. Schrader photographed the receding waves and the debris.[28] A shock was felt by one of the party, Mr. Baker, on shore and by natives. The water waves at this great distance from the earthquake origin may be ascribed to amplification of weak earth movements in the unconsolidated Pleistocene silts over which the Koyukuk River meanders here.[29]

In the Lisbon earthquake of 1755 the waters of Loch Lomond, in Scotland, at a considerably greater distance than this, were affected by water waves at the proper time.

Lower Yukon River.—At Russian Mission, or Ikogmute (figure 3), near the lower bend of the Yukon River, 730 miles northwest of Yakutat and over 300 miles from the place of observation by Mr. Schrader, a Russian priest, Father N. N. Amcan, felt this shock at 2 p. m. The date was not recorded by him, but it seems certain that it was the September 3d rather than the September 10th shock which he observed, because of the time of observation. It was a heavy shock and lasted long enough for one to run out of doors. The similarity of the unconsolidated Pleistocene silts at this point to those on the Koyukuk suggest the reason for sensible disturbances at this great distance from Yakutat Bay. This is the most remote point from the origin at which the earthquake shocks were sensible except to delicate instruments.

Résumé of September 3d earthquake.—This earthquake is known to have been felt at over thirty places (figure 3), the more remote of them as much as 730 miles from Yakutat Bay. The phenomena recorded include trembling of the earth, water waves, avalanches, etcetera, difficulty in standing up, and nausea. It is not definitely known where the origin was, but it has hitherto been assumed that it was in Yakutat Bay. The fact that there was probably faulting and uplift of the coast at Yakataga,

[28] Described in discussion at Geological Society of Washington, April 25, 1906, and in subsequent correspondence.

[29] See plate ix, opposite page 448, 21st Annual Report, U. S. Geological Survey, part II, 1899-1900.

100 miles west of Yakutat, suggest that the origin of this first shock might have been there. The nearness of Yakataga to the center of disturbance (figure 3) is not regarded as significant, since the centrum theory of earthquakes has been seriously questioned in recent years. More important is the fact that the prospectors in Disenchantment Bay seem to describe this shock as less severe than in the Chugach Mountains, etcetera, although we may be reading this interpretation into their accounts or they may have experienced such severe shocks afterwards (September 10) that the first shock seemed slight to them in contrast. The greater intensity at Yakutat Village than in Disenchantment Bay is doubtless due to the loose, unconsolidated rocks at the former place on Yakutat foreland, where shocks would be more severe than among the metamorphosed rocks of the mountains in Disenchantment Bay. The time records are not conclusive on this question, but the Yakataga origin is quite as possible as that at Yakutat.

After-shocks of the September 3d earthquake.—Light shocks between September 3d and 9th are recorded by Mr. Fults in Disenchantment Bay, Mr. Hill at Yakutat, Mr. Ritter at Cape Whitshed, and others, but no dates or times were recorded.

FIRST EARTHQUAKE ON SEPTEMBER 10, 1899

List of localities.—On Sunday, September 10, the first heavy shock occurred about twenty minutes of eight in the morning.[39] So far as known, it was recorded at the following places; the list is doubtless incomplete, because of the overshadowing violence of the second shock on this day:

Places.	Location with respect to Yakutat Bay.	Observers.
Disenchantment Bay ...	In Yakutat Bay.....	J. Bullman, L. A. Cox, A. Flenner, J. D. Fults, Jr., A. Johnson, T. Smith, and D Stevens.
Yakutat Village.....	Mouth of Yakutat Bay....	C. E. Hill, R. W. Beasley, Albin Johnson, and others.
Copper River delta.....	220 miles west-northwest.	H. P. Ritter, E. B. Latham, and others.
Chugach Mountains.....	240 miles northwest.....	W. C. Babcock.
Valdez	250 miles west-northwest.	L S. Camicia.
Upper Alsek River.....	90 miles east.....	A. E. Acland.
Upper Yukon River.....	190 miles northeast.....	Northwest mounted police.
Skagway.....	160 miles east-southeast...	B. F. Shelton and others.
Juneau.....	220 miles southeast.....	H. H. Folsom and others.

[39] Assuming an origin in Yakutat Bay, this began at 7h. 43m. 13s. (17h. 1m. 30s., Greenwich mean time), if based on distant seismograph records. Mr. Beasley's time record at Yakutat (7.40) agrees closely with this.

Disenchantment Bay.—In Disenchantment Bay this shock was severe enough to throw a man off his feet. There was movement of the ground and low shrubs shook and were bent as if in a strong wind.[31] There were less severe shocks all the forenoon, fifty of which were counted by Mr. Flenner, one of the prospectors.

Yakutat.—R. W. Beasley[32] and C. E. Hill[33] state that the early shock September 10, at Yakutat Village, made the one of the week before pale with insignificance. Lamps swung, trees swayed, houses creaked and groaned, sleeping people were awakened and rushed out of doors without dressing. The shock lasted 3 seconds. Mr. Hill gives the time as 8 a. m., and Mr. Beasley 7.40, the latter being thought correct because it agrees closely with the seismograph records, as does his time record for the heavier shock the same day.

More distant points.—At the Coast Survey camp at Cape Whitshed, on the Copper River delta, Messrs. Ritter and Latham describe the first shock as light but distinct, lasting a few seconds, at 7.43 a. m., local time, at Cape Whitshed (not the first shock). These times were obtained from a good and well-rated chronometer. The earth vibrated. The weather was calm and cloudy, with occasional showers. The after-shocks include one at 8.01; distinct continuous vibrations, lasting over 100 seconds, at 10h. 38m. 34s.; a shock which lasted 15 seconds and caused the camp flagstaff to vibrate violently, at 10h. 53m. 45s.; a shock violent at the beginning and tapering off toward the end, at 10h. 59m. 55s., the vibrations being continuous for 180 seconds and in a northwest-southeast direction, and a shock lasting 30 seconds at 11h. 5m. 5s.

In the Chugach Mountains Lieutenant Babcock felt a slight shock, lasting eight or ten seconds, at 7.08 a. m.; Dr. L. S. Camicia observed it at Valdez at 7 a. m. Ninety miles east of Yakutat, Sergeant A. E. Acland, of the Royal Northwest mounted police, at Dalton House, north of the Saint Elias Range, recorded it at 7 a. m. At another post, Carmacks, on the Yukon River, 190 miles northeast of Yakutat, it was observed at 8.15 a. m. At Skagway, Juneau, and other points observations of this earthquake were also made.

After-shocks, beside the fifty recorded in Disenchantment Bay, include many at Yakutat Village, fifteen or twenty at Dalton House north of the Saint Elias Range, ten or more at Cape Whitshed, five in the Chugach

[31] J. P. Fults, Jr.: Seattle Daily Times, September 28, 1899; New York Sun, September 29, 1899.
L. A. Cox: The Sitka Alaskan, October 14, 1899.
[32] The Sitka Alaskan, September 16, 1899.
[33] San Francisco Examiner, dispatch dated Seattle, September 21, 1899.

Mountains, two at Carmacks on the Yukon, five at Skagway, several at Juneau, etcetera. Of these after-shocks, those at Dalton House, 90 miles northeast of Yakutat Bay, lasted from 5 to 40 seconds; those at Cape Whitshed, 220 miles west of Yakutat, lasted 100 to 180 seconds.

THE GREAT EARTHQUAKE OF SEPTEMBER 10, 1899

General character.—The greatest earthquake of this series began at 12.22 p. m., local solar time, in Disenchantment Bay, near Yakutat, or 21h. 40m. 13s., Greenwich mean time.[34] It is practically certain that this is the shock in association with which the faulting and changes of

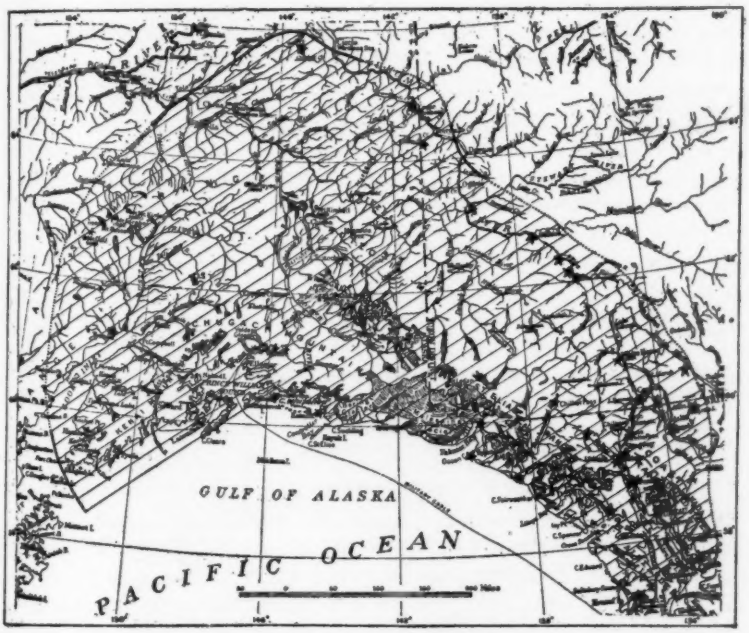

FIGURE 4.—*Map of Part of Alaska*

Showing minimum area within which the great Yakutat Bay earthquake of September 10, 1899, was felt. Stars at places of known observations

[34] The time of this shock has been variously stated. In earlier papers (Bull. Geol. Soc. Am., vol 17, 1905, p. 31, and Geographical Journal, July, 1906, p. 38) the time has been given as 3 p. m., based on a single statement by a local observer. It has also been stated by men on the ground as 12.15, 12.30, 1.20, 1.30, 1.50, 2 o'clock, etc., their timepieces varying in relation to solar time. The present figure is computed from the Coast Survey observation near the Copper River delta and distant seismograph records, and may be accepted as correct.

level of the coast took place. Everywhere within the sensibly shaken area this is reported as the most severe of the series, and this conclusion is supported by the seismograph records. The origin may be assumed to be near 59° 58′ 20″ north latitude and 139° 33′ west longitude.

List of localities.—So far as known, the shock was felt at the following places (see figure 4):

Places.	Location with respect to Yakutat Bay.	Observers.
Disenchantment Bay	In Yakutat Bay	J. Bullman, L. A. Cox, S. Cox, A. Flenner, J. P. Fults, Jr., A. Johnson, T. Smith, and D. Stevens.
Yakutat Village	Mouth of Yakutat Bay	C. E. Hill, R. W. Beasley, Mrs. Esther Early, Albin Johnson, and others.
Pacific Ocean	West of Yakutat	
Controller Bay	170 miles west of Yakutat.	T. G. White.
Copper River delta	220 miles west-northwest.	H. B. Ritter, E. B. Latham, and others.
Chugach Mountains	240 miles northwest	W. C. Babcock.
Chugach Mountains	250 miles northwest	J. D. Jefferson.
Valdez	250 miles west-northwest.	L. S. Camicia.
Homer	420 miles west of Yakutat	George Jammé.
Cook Inlet	410 miles west-northwest.	E. F. Glenn.
Birch Creek District	430 miles northwest	J. E. Kinnaley.
Eagle	340 miles north-northwest.	W. G. Myers.
Forty Mile District	290 miles north-northwest.	F. Dennison.
Stewart River	240 miles north	Lars Gunderson.
Fort Selkirk	215 miles north	
Five Fingers	200 miles northeast	Telegraph operator.
Tantalus	190 miles north	Northwest mounted police.
Upper Yukon River	180 miles northeast	J. J. McArthur.
Upper Yukon River	190 miles northeast	Northwest mounted police.
Whitehorse	170 miles northeast	G. S. Fleming.
Tagish	180 miles east	Telegraph operator.
Upper Alsek River	90 miles northeast	A. E. Acland.
Upper Alsek River	115 miles east	Prospectors.
Dry Bay	60 miles southeast	Charles Johnson.
Glacier Bay	150 miles southeast	August Buschmann.
Atlin Lake	215 miles east	J. C. Gwillim.
Atlin District	230 miles east	J. H. Pottinger.
Surprise Lake	240 miles east	John Bimms.
Teslin Lake	275 miles east	G. E. Boulter.
Skagway	160 miles east-southeast	C. L. Andrews, B. F. Shelton, and others.
Berners Bay district	180 miles southeast	H. W. Mellen.
Juneau	220 miles southeast	H. H. Folsom and others.
Sumdum	275 miles southeast	R. V. Rowe.
Sitka	260 miles southeast	P. T Rowe, Andrew Malakoff, and others.
Lake Chelan, Washington.	1,200 miles southeast of Yakutat Bay. Water waves perhaps due to this earthquake.	Residents of Chelan.

Disenchantment Bay.—In inner Yakutat Bay, near the junction of Russell Fiord and Disenchantment Bay, the great earthquake at noon was felt by the same eight prospectors who were there during the shocks of September 3 and early September 10. The testimony of these men—Messrs. Bullman, the two Coxes, Flenner, Fults, Johnson, Smith, and Stevens—is of great importance, as they were right in the midst of the faulted area on one old fault-line, and consequently at the very origin of the earthquake. Two of them have written accounts of their experience[35] and the author has talked with a third, Mr. Flenner. Their accounts agree well and seem in the main reliable.

They were in two camps (figure 5) on the moraine and alluvial fan of Variegated Glacier near the elbow in Yakutat Bay, where they were engaged in placer mining. They had made a contrivance of suspended hunting knives whose points touched and jingled when the earth trembled. With this they counted 52 shocks on September 10, culminating in the great earthquake at noon.

The shock was so severe that it was impossible to stand and two of the men who were in a tent held on to the pole to keep from being thrown to the ground, while a third fell over a stove in attempting to get outside. The land swayed and undulated and was broken along jagged cracks and moved up and down. This was estimated to have lasted two and a half or three minutes. Numerous fish were killed by the shock. The dam of a lake was broken and a flood washed down on the camp, burying part of it beneath rocky debris. A great water wave, which seemed to be 20 feet high, rushed upon the shore. Some of the men were washed high up on the moraine by this wave. There was a second wave 20 or 30 feet high. Avalanches descended the mountain slopes with deafening roar. The Hubbard Glacier, which is about two miles to the northwest and has a tidal front five miles across, was broken and great quantities of ice discharged into the fiord. A boat was smashed to kindling wood and most of the tents, provisions, bedding, and clothing were lost. A stream was diverted from one course on the alluvial fan, divided, and reunited again.

The men ran to and fro aimlessly, saving a few provisions and blankets, and eventually seeking shelter on the mountain side. They tied themselves to shrubs with strips of clothing and spent a disturbed afternoon and night, harassed by roaring avalanches, swollen streams, rain, occasional earthquakes, and anxiety as to the future. Their position was precarious, for they were cut off from retreat by land by the crevassed

[35] L. A. Cox: The Sitka Alaskan, October 14, 1899.
J. P. Fults, Jr.: Seattle Daily Times, September 28, 1899, and New York Sun, September 29, 1899.

Hubbard and Nunatak glaciers. No one knew of their being here, and for all they knew Yakutat might have been destroyed. One of their boats was smashed and the other washed away, as were all their sluices, and there was no driftwood or any timber large enough to make a raft.

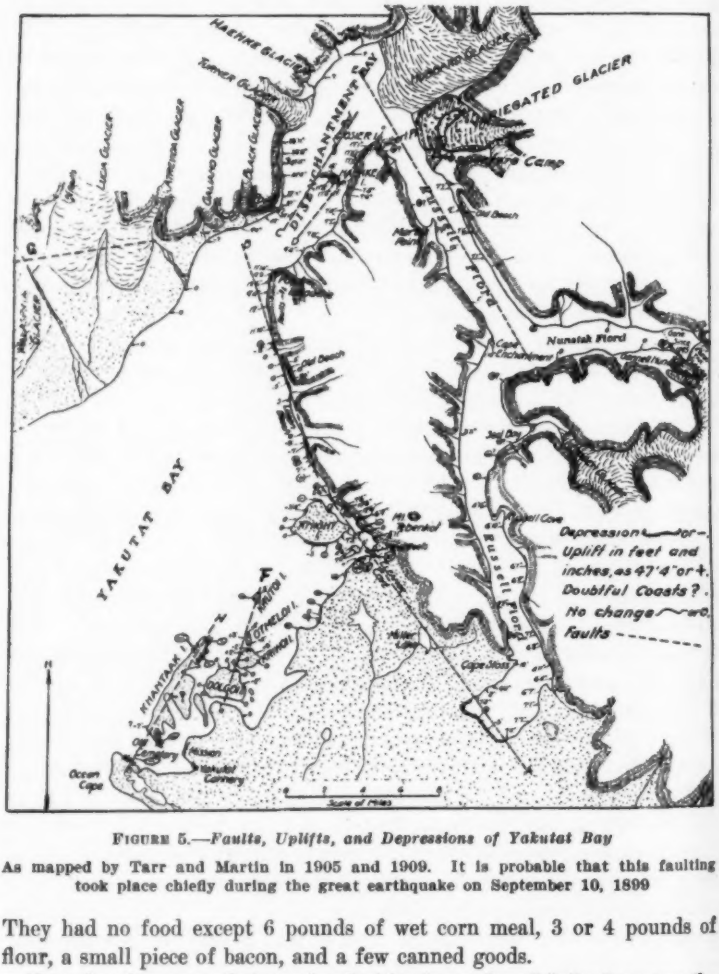

FIGURE 5.—*Faults, Uplifts, and Depressions of Yakutat Bay*

As mapped by Tarr and Martin in 1905 and 1909. It is probable that this faulting took place chiefly during the great earthquake on September 10, 1899

They had no food except 6 pounds of wet corn meal, 3 or 4 pounds of flour, a small piece of bacon, and a few canned goods.

Next day, however, their twelve-foot boat was found lodged among the alders, a damaged native canoe was picked up afloat in the fiord, the

scanty provisions were replenished from the abundance of dead fish washed up by the earthquake wave, and the men started for Yakutat Village, 30 miles distant.

Often the boats had to be carried bodily across the compact jam of icebergs, and it was only after several days' hard work that Yakutat was reached.

It was found in 1905 that the earth movement with which these earthquakes were associated was along seven or more fault-lines, involved the tilting and jostling of three or more blocks of the earth's crust in Yakutat Bay. Accompanying this were changes of level of the land including uplifts of 7 to 10 feet on the southeast side of the bay, 40 to 47 feet on the northwest side, as well as the submergence of coasts from 5 to 7 feet. One of the faults bounding these blocks is at least 30 miles long, another is over 17. Eight miles west of the prospectors' camp the coast was uplifted 47⅓ feet, two miles southeast there was a 7½-foot uplift, while at their camp there was no change of level. The distribution of these faults and changes of level is shown in figure 5. Along faults A, B, E, and F the movement was a renewal of faulting along old faults. Along several of the faults 4½ miles west of the prospectors' camp, new reefs were raised above sealevel. Seventeen miles southeast, near Nunatak Glacier, minor faulting broke a hill into strips, 29 step faults from a few inches to nearly 8 feet high being observed in 1905.

All these phenomena, more fully described elsewhere,[36] might be presumed to have taken place during the great earthquake at noon on September 10, because this is the only shock of this series which is known to have been accompanied by water waves in Disenchantment Bay or at Yakutat Village, and it is inconceivable that such notable faulting, elevation, and submergence could have taken place without great water waves. Dr. H. F. Reid has suggested that weak, unobserved water waves accompanied faulting along faults A and B during the early shock of September 10, and that the movement along faults C, D, E, F, G, and H caused the great earthquake of September 10, the September 3d faulting having been at Yakataga, as suggested above.

The avalanches during this and the other earthquakes of this series resulted in a brief spasmodic advance of the Galiano Glacier between 1899 and 1905,[37] followed by similar advances of the Variegated, Haenke, Atrevida, and Marvine lobe of Malaspina Glacier between 1905 and

[36] R. S. Tarr and Lawrence Martin: Recent changes of level in Alaska. Bull. Geol. Soc. Am., vol. 17, 1906, pp. 29-64, and in a professional paper of the U. S. Geological Survey in preparation.

[37] R. S. Tarr and Lawrence Martin: Glaciers and glaciation of Yakutat Bay, Alaska. Bull. Amer. Geog. Soc., vol. xxxviii, 1906, pp. 152-153.

1906,[38] and of Hidden, Lucia, and Hubbard glaciers between 1906 and 1909.[39]

Yakutat.—At the village of Yakutat, 30 miles from Disenchantment Bay, the great earthquake was observed, and has been described by Mr. Beasley,[40] the storekeeper; Mr. Hill,[41] a surveyor; Rev. Mr. Johnson,[42] the missionary; Mrs. Esther Early, a native woman; W. M. Rock,[43] a prospector, and many other whites and Yakutat natives.

Some of the facts mentioned below are also from correspondence and from conversations. The harbor and settlement at Yakutat is shown in figure 6.

Mr. Beasley states that the great earthquake came at 12.15, agreeing closely with the computed time records. It had a duration of five seconds. All the canned goods on the shelves and all the kettles, pails, and lanterns hanging from nails overhead were shaken to the floor of the store. There were waves in the ground and water waves in the bay.

Mr. Hill states that people were unable to walk or stand without holding to something. The church bell in its tower was rung by the tremors. Three great waves rolled into the bay at intervals of about five minutes, raising the level of the water 15 feet and nearly washing away some of the native houses. Mr. Beasley states that the water rose 8 or 10 feet in as many minutes. Mrs. Early observed that the water ran out a long distance before the coming of the first great wave.

After this shock all the inhabitants of Yakutat except Mr. Beasley lived in tents on the hills above town. There were 247 inhabitants at Yakutat in 1900 and presumably about the same number in 1899.

The residents agree that the old native cemetery on Khantaak Island was partly destroyed by subsidence during this earthquake (figure 6), which was along a fault-line (H, figure 5), as the linear arrangement of subsidence shows. Near Ocean Cape sand vents, or craterlets, developed during this shock, leaving holes 4 or 5 feet deep and scattering sand 6 inches deep over several acres. About ten acres in this vicinity were also affected by fissuring, looking as if plowed by great furrows about 4

[38] R. S. Tarr: Recent advance of glaciers in the Yakutat Bay region, Alaska. Bull. Geol. Soc. Am., vol. 18, 1907, pp. 257-286; and Professional Paper no. 64, U. S. Geological Survey, 1909.

[39] R. S. Tarr and Lawrence Martin: National Geographic Magazine, vol. xxxi, 1910, pp. 1-54.

Lawrence Martin: Popular Science Monthly, vol. lxxvi, 1910, pp. 293-305.

[40] R. W. Beasley: The Sitka Alaskan, September 16, 1899.

[41] C. E. Hill: Seattle Post-Intelligencer, September 23, 1899; San Francisco Examiner, dispatch dated Seattle, September 21, 1899; Toronto World, September 25, 1899.

[42] Rev. Albin Johnson: Report of Commissioner of Education, 1898-9, vol. 2, p. 1402.

[43] W. M. Rock: Victoria Semi-Weekly Colonist, October 12, 1899.

feet apart and 4 or 5 feet deep. A cloud of dust from an avalanche was seen from a distance.

In 1905 and 1909 we found drowned forests and other evidences of subsidence at a dozen places from 1 to 14 miles from Yakutat Village (figure 6), and the statement that water waves accompanied only this shock at noon September 10 suggests that the subsidence all came in connection with this one great earthquake.

The steamship *Dora* touched at Yakutat on September 12, 1899, and her crew and passengers brought the first news of the earthquake here to

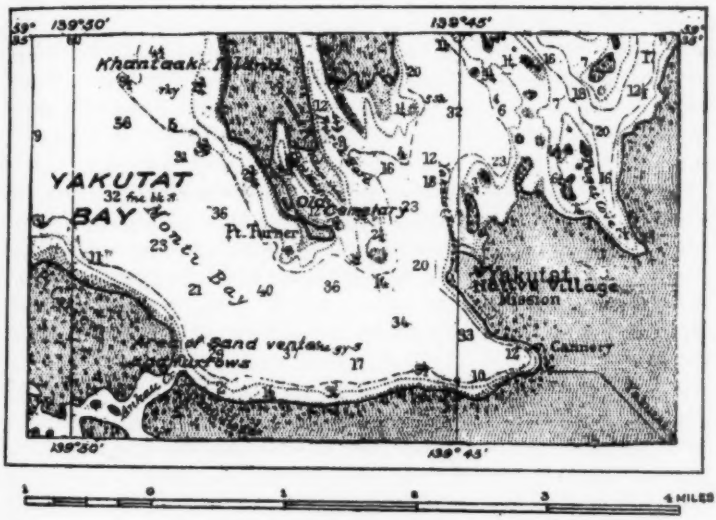

FIGURE 6.—*The Harbor at Yakutat Village*

Where submergence, water waves, and sand vents, or craterlets, developed during the great earthquake of September 10, 1899. Soundings in fathoms (after U. S. Coast and Geodetic Survey).

the outside world.[44] The United States revenue cutter *McCulloch* reached Yakutat on September 17. Capt. W. C. Coulson refers briefly to the earthquakes and to changes in the entrance to the harbor in the log of the vessel. The Governor of Alaska, Mr. Brady, went ashore and learned of the earthquakes, to which he refers incidentally in his annual

[44] Sitka Alaskan, September 16, 1899; San Francisco Examiner, dispatch dated Juneau, September 14, 1899; San Francisco Chronicle, dispatch dated Seattle, September 20, 1899; Seattle Daily Times, September 21, 1899; Butte Weekly Miner, September 21, 1899; New York Daily Tribune, September 21, 1899; same, September 22, 1899; New York Evening Post, September 21, 1899; Toronto Mail and Empire, September 22, 1899.

reports for 1899 and 1900.[45] Rev. Sheldon Jackson, the Commissioner of Education for Alaska, also gathered information regarding the earthquakes, to which he refers briefly in his diary[46] and in a somewhat exaggerated account published by the Associated Press.[47] A newspaper and magazine writer, W. J. Lampton, of the New York Sun, who also happened to be on the revenue cutter, interviewed the prospectors who had experienced the earthquakes in Disenchantment Bay.[48] Some numbers of the crew also described the earthquakes.[49]

Pacific Ocean west of Yakutat.—A severe storm at the time of the September 10 earthquake was felt by the revenue cutter *McCulloch* and was ascribed in the press to this earthquake.[50] Mr. Andrew Brown also experienced a very severe storm at sea between Kodiak and Sitka, on the steamship *Alliance*. No earthquake phenomena are reported, however, and these cases are cited merely to point out that the association by newspapers of these storms with the earthquakes is probably wholly without basis.

Controller Bay.—At Katalla, on Controller Bay, 170 miles west of Yakutat, Mr. T. G. White reports that the shaking was so strong on September 10 that one could not stand. Avalanches fell, trees waved on a calm day, a water wave 4 feet high went up the Bering River. An oil spring is said to have started flowing and oil is reported to have been seen in large amounts afterwards on the surfaces of streams and ponds near Katalla.[51]

Cape Whitshed.—At the Coast and Geodetic Survey camp near the Copper River delta and 220 miles west of Yakutat, Mr. Ritter and Mr. Latham observed the great earthquake at 11h. 58m. 33s. true local time, recorded by a good and well-rated chronometer. It lasted three minutes. There was violent shaking all the time; part of the time one way, then another. It seemed rotary. The top of a 40-foot flagstaff vibrated from 1 to 4 feet, and people had to stand with their heels at least 8 inches apart to keep from falling. It was impossible to stand with the heels together.

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[45] Department of the Interior, Misc. Repts., House Document 5, 56th Congress, 1st session, part ii, p. 29; House Document 5, 56th Congress, 2d session, part ii, p. 25.

[46] Ninth Annual Report on the introduction of domestic reindeer into Alaska. Government Printing Office, Washington, 1900, p. 50.

[47] Sitka Alaskan, September 23, 1899; San Francisco Examiner, September 25, 1899; London Times, September 26, 1899; Victoria Semi-Weekly Colonist, September 28, 1899; Portland Weekly Oregonian, September 29, 1899; Japan Times, Tokio, October 31, 1899.

[48] New York Sun, October 1, 1899.

[49] Seattle Daily Times, September 28, 1899.

[50] Seattle Daily Times, September 28, 1899.

[51] G. C. Martin: Bull. no. 335, U. S. Geological Survey, 1908, p. 117.

The plumb bob kept swinging slightly. There were at least four after-shocks and the earth vibrated practically all day. The after-shocks came at 12h. 7m. 8s., at 5h. 36m. 8s., at 5h. 44m. 2s., and the final one at 5h. 51m. 41s. The last one was stronger than those preceding.

The topographic effects within a radius of 10 to 15 miles of this camp, observed while making soundings and surveying shorelines on the Copper River delta during and after these earthquakes, consisted only of the sliding down of an occasional overhanging tree or soft bank or the soft portion of an overhanging rocky bluff.[52]

Chugach Mountains.—In the Chugach Mountains, 240 miles northwest of Yakutat, Lieutenant Babcock and the army officers building the military trail observed the great earthquake at 10.45 a. m.[53] It lasted a minute and ten seconds. Avalanches probably attended it, for peculiar reports similar to those of the preceding Sunday were heard.

In another part of the Chugach Mountains, about 55 miles east of Valdez Inlet, Mr. J. D. Jefferson, assistant postmaster at Valdez, who was encamped on Fall Creek, saw the trees and mountains swaying. A tent pulled and strained at its ropes. There was a great avalanche. What is described as a sickened feeling came over the observers.

At Valdez Village, still farther west, Dr. L. S. Camicia was so dizzy that he could not stand. A tidal wave 7 feet high came in from the sea.[54] The flagpole and the tops of trees vibrated.[55] Valdez had a population of 315 in 1900 and presumably about the same in 1899.

Kenai Mountains.—At Homer, on the end of a long sand spit in Kachemak Bay, Mr. George Jammé, a mining engineer, observed the great earthquake on September 10 at a point 420 miles west of Yakutat. He had arranged a swinging plumb bob after the shocks of the preceding Sunday, and observed that during this earthquake the bob swung in an ellipse with axes 9 and 17 inches long, the longer extending northwest-southeast.

Cook Inlet.—At Ladds Station, 5 miles north of Tyonek and 410 miles northwest of Yakutat, Lieut. E. F. Glenn, of the U. S. Army, felt the earthquake while eating. It was very severe, lasting long enough for him to walk out of a frame building, and it was perceptible afterward. The building rocked back and forth and every person or animal staggered or reeled.

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[52] Annual Report U. S. Coast and Geodetic Survey, Washington, September, 1901, p. 206.

[53] Diary of Lieutenant Babcock.

[54] Seattle Daily Times, September 29, 1899.

[55] Philipp Giesener: Personal communication.

Upper Yukon Valley.—In the Birch Creek district, west of Circle and about 430 miles northwest of Yakutat, Mr. J. E. Kinnaley felt an earthquake September 11, 1899 (probably September 10), which lasted long enough for one to run 20 feet. The ground seemed to be moving and sinking at the same time. There was a landslide at Pitkas Bar, on Birch Creek. Twenty miles distant, on Independence Creek, the water was thrown out of a sluice-box.

At Eagle, 340 miles north of Yakutat, the U. S. Weather Bureau observer, Judge W. G. Myers, felt the September 10 shock at 12.15 p. m. This is stated to be 141st meridian time, based on observations of the sun every few days. The shock lasted three or four seconds, jarring suspended mercurial barometers against rings at the bottom, beside causing poles to vibrate, lamps to swing, and tin plates on shelves to rattle.

In the Forty-Mile district, 290 miles north of Yakutat, Mr. F. Dennison reports a shaking of the ground observed by a number of prospectors in and near Jack Wade Creek. The exact date in September, 1899, was not recorded, but it may safely be presumed to be the 10th rather than the 3d because of the time of the shock, about noon.

Klondike Trail.—At the mouth of Stewart River, on the Yukon, 240 miles north of Yakutat, Judge Lars Gunderson, United States commissioner, felt very light shocks during the first ten days of September, 1899. People noticed clothes swinging gently from lines inside their houses. Many persons were dizzy.

At Fort Selkirk, where the Lewes and Pelly rivers unite to form the Yukon, and 215 miles north of Yakutat, one of these shocks in September, 1899, is said to have been felt, the date and hour not being recorded.

At Five Fingers rapids in the Lewes River, the Canadian telegraph operator wired to Whitehorse on September 10, shortly after 1.30 p. m., that he had just felt the great earthquake.

The foreman of a party engaged in building a winter trail near Five Fingers rapids relates that they were having lunch near the new telegraph line and had their attention attracted to the earthquake by the violent swaying of the wire and the heaving of the trees. Several men were seized with vertigo and the distant booming sound caused great consternation.

At Tantalus, or Carmacks, near 62° 6′ north latitude and 136° 15′ west longitude, 190 miles north of Yakutat, the earthquake was recorded September 10 in the post diary of the Tantalus detachment, Royal Northwest mounted police, at 11.45 a. m., as a rather severe shock. This time record is probably more nearly correct than that at Five Fingers, near by. Strong after-shocks were felt at 11.55 a. m., at 12.30 p. m., and at 12.45 p. m.

Along the Upper Yukon or Lewes River, near the mouth of Nordenskiold River, 190 miles north of Yakutat, Mr. J. J. McArthur, in charge of the telegraph line, did not feel this earthquake personally, probably because he was travelling on horseback, although his men working on the winter trail did. He did hear an irregular succession of loud detonations like the booming of cannon, and thought it was blasting. It may have been the fall of avalanches. He followed a trail from which his axemen had removed fallen timber that morning and found that trees up to 12 inches in diameter were overturned across the trail by the swaying motion of the earthquake. There was no wind at the time.

At Whitehorse, south of Lake Lebarge and 170 miles northeast of Yakutat, Mr. G. S. Fleming, the government telegrapher, reports that the severe earthquake September 10 came at 1.30 p. m., lasting between 45 and 60 seconds. Windows and dishes rattled; water splashed out of a pail; people rushed out of a log cabin, but had no difficulty in walking. Several waves crossed the river and dust rose from falling river bluffs. The motion of the earth was gradual. H. E. Porter observed trees swaying overhead on a perfectly still noon.

At Tagish, on Lake Bennett, 180 miles east of Yakutat, this shock was also felt and reported by telegraph to Whitehorse, 50 miles northward. The level of Lake Bennett is said to have been disturbed.

At Caribou Crossing, Bennett, White Pass, and various other points on the trails in Yukon Territory between Lake Bennett and the Klondike district, the earthquake was also felt,[56] the information being often indefinite as to date, place, etcetera, or exaggerated in details.

North of Saint Elias Range.—At Dalton House, Yukon Territory, east of the Alsek River, near 60° 6′ 30″ north latitude and 137° 4′ west longitude, about 90 miles northeast of Yakutat Bay, the great earthquake was felt by Sergt. A. E. Acland, of the Royal Northwest mounted police. It came about noon and lasted fully a minute. A log cabin was so severely shaken as to be unsafe; trees and flagpoles vibrated like a snapped whip; water spilled out of the east and west sides of wash dishes and pails; kitchen utensils swung on their nails; plates and cups were shaken off shelves; horses grazing two miles away came home at a gallop, frightened and snorting. There were heavy noises from the southwest, resembling far-away explosions or rumbling of thunder, thought by Mr. Acland to be due to shifting of glaciers in the Alsek Valley, but perhaps caused by avalanches. The motion was a gentle shaking at first, growing gradually more severe and then dying away. The men had to brace their knees in order to keep from falling.

[56] Victoria Semi-Weekly Colonist, September 25, 1899; Seattle Weekly Times, September 27, 1899; same, October 4, 1899.

At Glacier Camp, on the Dalton trail, north of the Saint Elias Range and 115 miles east of Yakutat, two men were building a cabin, one of whom was shaken off the log he was placing on the wall by the earthquake.

Dry Bay.—At the mouth of the Alsek River, 60 miles southeast of Yakutat, information collected for the writer by Charles Johnson indicates that the Dry Bay natives felt this September 10 earthquake as a much more severe one than that of the preceding Sunday. They were unable to stand up during the heaviest shaking and some of their houses were damaged by the earthquake.

Glacier Bay.—In this inlet, 150 miles southeast of Yakutat and famous as the location of Muir Glacier, the earthquake was observed by Mr. August Buschmann, superintendent of the Bartlett Bay salting station. He observed two shocks, not recording the exact time. They seemed to come from the westward. One lasted ten seconds, the other five seconds. They caused a trunk to move several inches on its casters and empty barrels to fall from beams overhead in the fish-house. An old man, walking up the beach, nearly fell during the earthquake.

The flow of icebergs from Muir Glacier increased many fold, the amount of drift ice in Glacier Bay making navigation for the small cannery steamers very difficult, as Mr. Buschmann observed.

The increase of floating ice and damage to Muir Glacier was noticed at once[57] in Glacier Bay and Icy Straits. It was commented on by the members of the Harriman Expedition,[58] and has been accompanied by a great recession of glaciers. Prof. H. F. Reid has recorded the retreat of Muir and adjacent glaciers.[59] Supt. O. H. Tittmann, of the U. S. Coast and Geodetic Survey, observed the floating ice on July 29, 1900, on the steamship *Queen*. Other vessels attempting to reach Muir Glacier in 1901 and 1902 were turned back by the floating ice in greatly increased amounts. The Muir Glacier receded between 2½ and 3 miles between 1899 and 1903;[60] it continued to retreat through 1906;[61] by 1907 it had receded about 8 miles from its position before the earthquakes in 1899.[62]

[57] Victoria Semi-Weekly Colonist, October 2 and October 12, 1899; Scientific American, vol. lxxxi, 1899, pp. 405-406.

[58] John Burroughs: Harriman Alaska Expedition, vol. i, p. 89.

G. K. Gilbert: Harriman Alaska Expedition, vol. iii, pp. 23-25; National Geographic Magazine, vol. xiv, 1903, p. 445.

[59] Variations of glaciers. Journal of Geology, vol. ix, 1901, p. 253; x, 1902, p. 317; xi, 1903, p. 287; xii, 1904, pp. 258-260.

[60] C. L. Andrews and W. H. Case: National Geographic Magazine, vol. xiv, 1903, pp. 441-444.

[61] F. E. and C. W. Wright: Journal of Geology, vol. xvi, 1908, pp. 52-53.

[62] Otto Klotz: Geographical Journal, vol. xxx, 1907, pp. 419-421.

Fremont Morse: National Geographic Magazine, vol. xix, 1908, pp. 76-78.

During this same period from 1899 to 1907 Grand Pacific Glacier had retreated 8½ miles and the other ice-tongues of Glacier Bay smaller amounts.[63] Since Mr. Buschmann has testified that the increased flow of icebergs began with the September 10 earthquake, we may safely ascribe the initiation of the rapid retreat and loss of scenic beauty of the Muir Glacier to this shaking in connection with the Yakutat Bay earthquakes.

Canadian Coast Range.—At Atlin and Discovery City, British Columbia, in the Canadian Coast Range, about 215 to 230 miles east of Yakutat, the severe earthquake was felt in several mining camps on September 10,[64] as well as at the Hudson Bay post near Teslin Lake,[65] 275 miles east of Yakutat Bay.

On the southeast shore of Atlin Lake, Prof. J. C. Gwillim, of the Canadian Geological Survey, made the best of these earthquake observations.[66] The shock came at 12.45 p. m., local meridian time, corrected by a latitude observation on the sun at noon on that day. There was an undulating motion lasting about 30 seconds. Water was spilled out of small utensils being used at dinner. There was a heavy wind, so no earthquake water waves could have been detected on Atlin Lake.

In the Surprise Lake district, east of Atlin, British Columbia, there were earthquake shocks during the first half of September, 1899, the heaviest shock coming on September 10. Mr. John Bimms[67] observed what he interpreted as smoke from a supposed volcano, but what may have been dust from great avalanches in this part of the Canadian Coast Range. Certain glaciers were broken.

Lynn Canal.—At various points along this fiord and in the mountains near by, the great earthquake of September 10, together with those of the preceding Sunday, was felt by a great many people. Since Skagway, Haines Mission, Dyea, Pyramid Harbor, and Juneau are steamer landings, and as Skagway was connected by telegraph with Vancouver and Seattle, these observations were reported in a great many newspapers. The accounts[68] are of variable completeness and accuracy.

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[63] Compare U. S. Coast and Geodetic Survey Charts 3095 (1899) and 8306 (1910).

[64] Victoria Semi-Weekly Colonist, October 2, 1899.

[65] Reported by Mr. Archibald Ainslie.

[66] Summary Report for 1899, vol. xii, Annual Report Geological Survey of Canada, p. 62A.

[67] San Francisco Chronicle, October 5, 1899.

[68] Seattle Daily Times, September 20, 1899; same September 21, 1899; same, October 2, 1899; Seattle Weekly Times, September 27, 1899; same, October 4, 1899; Victoria Semi-Weekly Colonist, September 21, 1899; same, September 25, 1899; San Francisco Chronicle, September 22, 1899; Chicago Daily Tribune, September 23, 1899; Portland Weekly Oregonian, September 29, 1899; San Francisco Chronicle, October 5, 1899; Sitka Alaskan, October 7, 1899.

At Skagway, 160 miles east of Yakutat, Rev. B. F. Shelton reports six or seven shocks between 4 a. m. and 3 p. m. on September 10. The one at 11.40 alarmed the people in church, the vibrations increasing until every one felt the motions distinctly in their seats.

The shock at 12.40 (the great earthquake) was so violent that persons walking were thrown against the walls and it was necessary to cling to supports to keep from falling. There were earth-waves, causing a nausea like seasickness upon the ocean, especially among the women and children. People had a strange, pallid, half-frightened look, locally known as "the earthquake face." Lamps swayed violently, electric lights swung nearly to the ceiling, pictures rebounded from the wall, glass windows vibrated, crockery was knocked from shelves and some plaster fell, and gaps were opened in walls. C. L. Andrews, the deputy collector of customs, observed that the shock lasted long enough for him to take two children by the hand, run out of the office 25 feet down a hall, one story downstairs, and out into the street.

Skagway had a population of 3,117 in 1900, and presumably about the same number in 1899. It was the most severely shaken large town in the disturbed area, but had no loss of life or serious damage to property, largely because the dwellings were chiefly low frame structures, log cabins, and tents. An earthquake of this magnitude in New York or Chicago or San Francisco, with their brick and stone structures and tall office buildings, would have wrought tremendous damage to life and property.

In the Berners Bay district, on the east side of Lynn Canal and 180 miles southeast of Yakutat, Mr. H. W. Mellen, a mining engineer, observed the September 10 earthquake at the Jualin mine. There were two shocks, fifteen minutes apart, about 12.30 p. m. The first was a little the more severe, lasting long enough for a man to go into his office, pick up overturned lamps, come out, and walk 50 feet. The second lasted long enough for him to run 75 feet into a mine tunnel, call the miners, and run out again. The motion was severe enough to make a raincoat swing outward a foot from the wall on which it was hanging, to upset lamps, break dishes, slide a 24-inch book off a table, and make a man fall off a chair. Hard shaking came first, followed by undulations. There were distinct earth-waves, making people stagger in walking. Avalanches were heard. The direction of staggering in walking and of sliding of books and dishes indicated that the shock came from the northwest—that is, from the direction of Yakutat.

At Juneau, near the entrance of Lynn Canal and 220 miles southeast

of Yakutat, the great shock of September 10 was also felt.[69] Judge H. H. Folsom, the United States commissioner, recorded this shock at 12.55 p. m. It lasted long enough for him to get out of a barber's chair, walk 20 feet to the sidewalk, and watch electric light poles sway. Buildings were shaken severely, especially the hotel, hospital, and churches, but no serious damage was done. Frightened people ran into the streets. Miners emerged hastily from the Treadwell gold mine at Douglas. Douglas and Juneau together had 2,689 inhabitants in 1900 and presumably about the same the year before, and only low wooden buildings. There were minor tremblings all day and another severe shock between 4 and 5 p. m.

Southeastern Alaska.—In Taku Inlet, southeast of Juneau, the earthquake was probably severe,[70] damaging the glaciers so that increased iceberg discharge began at once, as in the Glacier Bay and Icy Straits regions. Several of the fiords of the Inside Passage,[71] including Lynn Canal, Taku Inlet, Stephens Passage, and Gastineau Channel, were obstructed by ice. This resulted temporarily in difficulties in navigation, one vessel, the *Rosalie*, being damaged by collision with floating icebergs. The Taku Inlet glaciers seemed in 1905 to have recovered from their 1899 losses.[72] The net advance of Taku Glacier between 1890 and 1905, as proved by photographs,[73] may possibly be ascribed to earthquake avalanching in 1899, the snowfield being so augmented that although the tidal ice-front temporarily retreated, because of shaking and water disturbances, the glacier itself has eventually advanced, as those in Yakutat Bay have done.

At Sumdum, in southeastern Alaska, 275 miles southeast of Yakutat, Mr. R. V. Rowe, a carpenter, observed an earthquake on an unrecorded date in September, 1899, which caused a building he was erecting to rock for about ten seconds.

In McHenry Inlet, Etolin Island, Alexander Archipelago, 375 miles southeast of Yakutat, Mr. Fred Patching reports a sharp earthquake about 6.30 a. m. a Sunday morning in September, 1899, in connection with which great landslides occurred. This location is detached from the main shaken area and, because doubtful, has not been put on the map.

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[69] Seattle Daily Times, September 20, 1899; San Francisco Examiner, dispatch dated Juneau, September 14, 1899; New York Evening Post, September 21, 1899; New York Daily Tribune, September 22, 1899.

[70] Seattle Daily Times, September 22, 1899; San Francisco Examiner, dispatch dated Seattle, September 21, 1899.

[71] Victoria Semi-Weekly Colonist, September 25, 1899; same, October 12, 1899; Seattle Daily Times, September 21, 1899; same, September 22, 1899; Scientific American, vol. lxxxi, 1899, pp. 405-406; Current Literature, vol. xxvii, 1900, p. 123; xii Annual Report Geological Survey of Canada, 1899, p. 62A.

[72] H. F. Reid: Journal of Geology, vol. xiii, 1905, p. 317.

[73] H. F. Reid: Variations of Glaciers, Journal of Geology, vol. xiv, 1906, p. 408.

At Sitka, 260 miles southeast of Yakutat, the great earthquake of September 10 was sensible,[74] though rather slight. Bishop P. T. Rowe, who was lying down, was among those who felt it. Dr. C. C. Georgeson, who was walking out of doors, did not. Sitka was near the outer limit of the sensible shock in this direction, and from several towns near by, in southeastern Alaska, specific statements have been received that these earthquakes were not felt.

Lake Chelan, Washington.—On the east side of the Cascade Mountains, in the State of Washington (latitude about 47° 50′ north, longitude about 120° west), water waves were observed on Lake Chelan at the time when the tremors of the great earthquake of September 10 were traversing the region. Lake Chelan is nearly 1,200 miles from Yakutat Bay, Alaska (figure 1). The waves, observed on at least four points of the coast of this long, narrow lake, arose at about 2 p. m.[75] on an otherwise glassy lake, there being no wind. They rose 15 or 20 feet, driving a boat ashore and lasting nearly two hours.

The earthquake originated at Yakutat at 12.22 (about 1.40 on Lake Chelan). Transmission would occupy ten to twenty minutes or more. The seismograph at Victoria, British Columbia (figure 1), recorded this shock at 1.45[76] (equivalent to 1.59 at Chelan). The first waves were noted "at about 2 o'clock."

The phenomena might, of course, be due to (*a*) landslides or (*b*) a secondary earthquake. In the absence of evidence of these, there is no particular reason to doubt that the weak tremors were in some way naturally amplified in this long, deep, mountain valley, so that earthquake water waves were caused. In the Lisbon earthquake of 1755 water waves on lakes and ponds in England and on Loch Lomond, in Scotland, attended the shocks and at an even greater distance than from Lake Chelan to Yakutat Bay.

Résumé of the great earthquake of September 10.—This earthquake is known to have been felt at more than forty places (figure 4), varying in distance from 2 miles to 430 miles from the origin in Yakutat Bay. Water waves were probably caused nearly 1,200 miles away. The observations include earth movement, faulting, water waves, floods, avalanches, fissures, spouting from sand craterlets, difficulty in standing and walking, damage to buildings, a cemetery, etcetera, terror on the part of ani-

[74] The Sitka Alaskan, September 16, 1899; Seattle Daily Times, September 28, 1899.

[75] San Francisco Chronicle, September 15, 1899; Salt Lake Semi-Weekly Tribune, September 19, 1899. Information obtained from C. E. Rusk, of Chelan, in 1909.

[76] Interview with Mr. Napier Denison, the Government observer, in the Victoria Semi-Weekly Colonist, September 21, 1899. Unfortunately this valuable seismograph was subsequently lost in the mails.

mals as well as man, and nausea. Shorelines were uplifted as much as 47½ feet and depressed as much as 5 feet in Yakutat Bay. New reefs were uplifted. Shattering of ice-fronts caused increased iceberg discharge for many tidal glaciers. Muir Glacier subsequently retreated 8 miles in 8 years. Avalanches caused a series of glacier floods, after an interval dependent on the length of the ice-tongue. Seven or more glaciers near Yakutat Bay had brief spasmodic advances with enormous crevassing within ten years, including part of Malaspina Glacier. The front of Hidden Glacier has advanced over two miles. There was no loss of life and scarcely any damage to property within the shaken area.

EARTHQUAKES OF SEPTEMBER 11 TO 29, 1899

Light after-shocks were felt at Yakutat all through the night of September 10 and others during the remainder of the month.

On the 11th a few slight shocks were noted at the Cape Whitshed Coast Survey camp near the Copper River delta. The earthquakes felt between the 12th and 16th were not precisely recorded, because the uproar of heavy storms then raging made it hard and uncertain to determine time and duration.

On September 15 severe shocks at 7.15 and 7.30 p. m. at Yakutat caused R. W. Beasley's lamps to swing and kettles to beat against each other, lasting long enough for him to run out of doors. At Skagway[77] the shocks came at 8.20 and 8.40 p. m., the first lasting 50 seconds. It caused electric lights to sway 18 inches and stopped pendulum clocks. Some houses moved; a pier and several houses were damaged; men staggered in walking. The shocks were reported by telegraph from Lake Bennett, on the Klondike trail.

On September 17 a shock was felt at Skagway, but not at Yakutat or Cape Whitshed.

On September 23 eight shocks were felt at Cape Whitshed; that at 1.22 a. m. lasted 2 minutes—long enough for a man to jump out of cot and light candles. It woke the Coast Survey party from sleep, causing a plumb bob to vibrate with half-second oscillations with an amplitude of 10 inches from northwest to southeast. It consisted of a short shock, followed after a few seconds by one of longer duration. The after-shocks came at 1h. 28m. 9s., lasting 2 seconds; at 1h. 3m. 9s. with equal duration; at 1h. 40m. 9s., consisting of two short shocks of a second each; at 1h. 41m. 51s., consisting of two shocks lasting a quarter of a

[77] Seattle Post-Intelligencer, September 23, 1899; Chicago Daily Tribune, September 23, 1899; Victoria Semi-Weekly Colonist, September 25, 1899; Seattle Weekly Times, October 4, 1899.

second each. Shocks were also felt on this date at Cordova and Valdez, on Prince William Sound, and at Sitka.

On September 26 four shocks were felt at Cape Whitshed, one of them at 2.40 a. m., during a rain-storm, waking sleeping men; one at 12h. 5m. 38s. p. m., lasting half a minute. There was a short shock at 2.46 p. m., and another during the night. One of these earthquakes seems also to have been felt at Eagle.

On September 29 the last earthquake of the series was sensible at Cape Whitshed during the night, the Coast Survey observers feeling none others before they left the Copper River delta on October 23. Light after-shocks were felt at Yakutat, however, all winter.[78] R. W. Beasley lists them as occurring December 14, 20, and 28, 1899; January 12 and 27, and February 16, 1900.

Seismograph Records

Study by seismologists

As has been pointed out by Dr. G. K. Gilbert,[79] this series of Yakutat Bay earthquakes is of importance because it belongs in the rather small group of adequately observed great shocks. "It ranks high in the scale of energy, the position of its origin has been determined with unusual precision, and its initial time is known with close approximation." More than this, it is an abnormal group of shocks[80] in its departure from the normal sequence of (1) prelude, (2) great shock, and (3) after-shocks. This group (figure 7) perhaps had no prelude (August 27?); there were at least four great shocks (September 3, 10, 10, 23); several other important ones (September 15, 17 (?), 26), and a long series of after-shocks.

The seismograph records at Victoria, British Columbia (figure 1), the station nearest to Yakutat where precise instrumental observations were made, were first noticed, while the earthquakes were still in progress, in newspaper interviews with Mr. Napier Denison.[81] Afterwards these world-shaking earthquakes were studied by experienced seismolo-

[78] Rev. Albin Johnson: Report of Commissioner of Education for 1898-9, vol. 2, 1900, p. 1402.

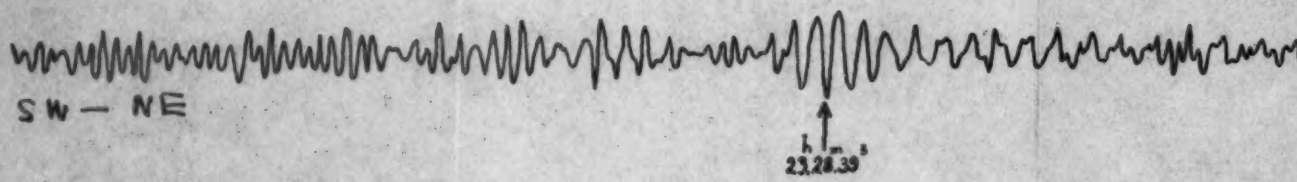
[79] Preface to report on the Yakutat Bay (Alaska) earthquakes of September, 1899, by R. S. Tarr and Lawrence Martin, in Professional Paper of the U. S. Geological Survey (in preparation).

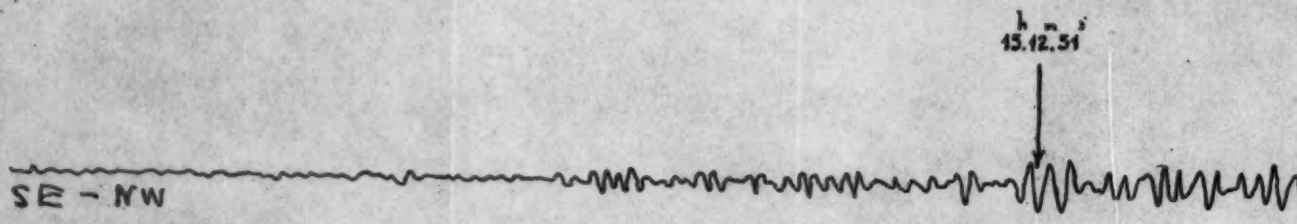
[80] G. K. Gilbert: Earthquake forecasts. Science, N. S., vol. xxix, 1909, pp. 126-127.

[81] Victoria Semi-Weekly Colonist, September 21, 1899; same, September 28, 1899; Chicago Times-Herald, September 25, 1899; New York Daily Tribune, September 25, 1899; San Francisco Examiner, September 25, 1899.

Seismograms of the great Yakutat

as recorded at C





Seismograms of the San Francisco,

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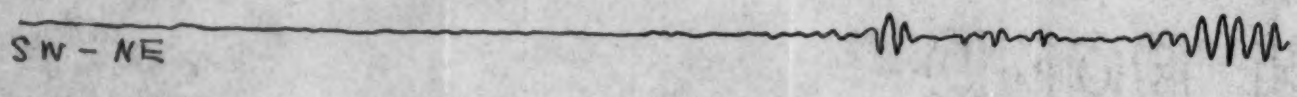
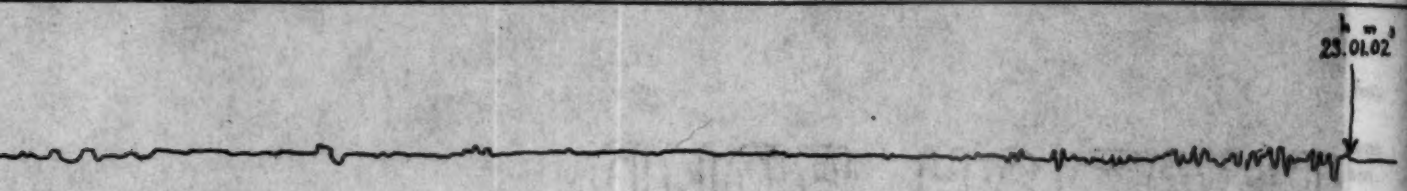
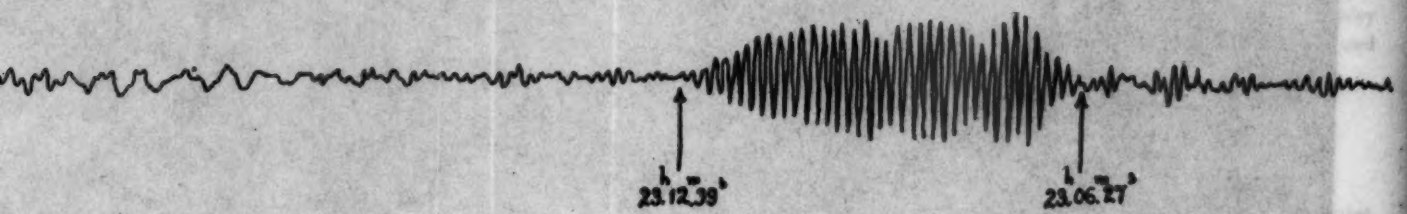


COMPARISON OF ONE OF THE YAKUTAT BAY EARTHQU



at Bay earthquake, Sept. 10. 1899

Catania, Italy.



, California, earthquake Apr. 18. 1906

at Catania, Italy.

gists like Prof. John Milne,[82] Dr. F. Omori,[83] Dr. A. Cancani[84] and other Italian observers, Prof. E. Lagrange,[85] Dr. R. D. Oldham,[86] and others.

In 1900 the British Association for the Advancement of Science published 28 of the better seismograms of the Yakutat Bay earthquakes of September 3, 10, and 23, 1899.[87] The seismogram of the September 10 disturbance at Batavia, Java, is reproduced by Dr. J. P. van der Stok in an article, "Two earthquakes in Europe and at Batavia."[88] The Imperial Earthquake Investigation Committee of Japan published records of the September 3d and 10th shocks as recorded at the Tokio observatories of Hongo and Hitotsubashi.[89] The seismogram of the September 3d earthquake as recorded at Uccle, Belgium, was published in 1901.[90] The September 3d record of the nearest seismograph to Victoria, British

FIGURE 7.—*Earthquake Diagram*

Showing relative time intervals and approximate relative intensities of the eight most severe earthquakes at Yakutat Bay, Alaska, in September, 1899

Columbia, and, therefore, only 1,000 miles from Yakutat, and the Toronto records of the earthquakes of September 3 and 10 were reproduced by Dr. R. F. Stupart,[91] of the Meteorological Service of Canada.

Plate 29 shows the Catania records of the great earthquake of Septem-

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[82] J. Milne: Report of British Association for the Advancement of Science, 1900, pp. 64, 66, 68, 69, 70, 71, 72-73, 74, 77, 80, 82, 87, 95, 96-97, 98, 99, 100, 105, 108, and plates ii and iii; same, 1902, pp. 62, 64.

[83] F. Omori: Publications of Earthquake Investigation Committee in foreign languages, no. 5, Tokio, 1901, pp. 21, 26, 37, 38, 39, 40, 47, 48, 49, 50, 59, 62, 63; same, no. 6, 1901, 47-48, 49-50, 50-51, 51-52; same, no. 13, 1903, 87, 88, 96-99, 112, 114, 117, 121, 122, 123; same, no. 21, 1905, 45-49, 60, 71, 76, 77, 79, 80, 81, 85, 88, 89.

[84] A. Cancani: Noticie sui terremoti osservati in Italia durante l'anno 1899. Appendice al Bollettino della Societa Sismologica Italiana, vol. 6, Modena, 1900-1901, pp. 178-190, 194-198, 199-208, 223-227.

[85] E. Lagrange: Les Movements Sismiques en Belgique en 1899. Bull. de la Soc. Belge d'Astronomie, 5me. année, 1901, no. 2, p. 4.

[86] R. D. Oldham: Quarterly Journal of the Geological Society, vol. lxii, 1906, pp. 459, 461, 471.

[87] Fifth Report, Committee on Seismological Investigation, British Association for the Advancement of Science, 1900, pp. 95-97, 100.

[88] Koninklijke Akademie van Wetenschappen te Amsterdam. Proceedings of the Section of Sciences, vol. ii, 1900, plate opposite page 246.

[89] Publications of Earthquake Investigation Committee in foreign languages, no. 5, 1901, plates vii and viii; same, no. 21, 1905, plate xxxvi.

[90] Bull. Société Belge d'Astronomie, 5me. année, 1901, no. 2, plate xii.

[91] Proceedings and Transactions of the Royal Society of Canada, second series, vol. ix, section iii, 1903, plate opposite page 71.

ber 10, 1899, at Yakutat Bay. In order to compare the duration and magnitude of this Alaskan earthquake with that of San Francisco, California, the record of Catania is also shown. The distances being nearly equal and the paths equivalent, a direct comparison may be made. These show the records from instruments in two planes at right angles and are from heavily weighted vertical pendula with mechanical registration. Records of the Omori horizontal pendula at Tokio as affected by the earthquakes of September 3 and 10 are shown in plate 30.

LOCATION OF ORIGIN FROM SEISMOGRAMS

As early as September 27, 1899, Prof. John Milne located the origin of the earthquakes of September 3 and 10 in Alaska.[92] He later made the more specific location in the Pacific Ocean west of Alaska, near latitude 50 degrees north and longitude 150 degrees west, noting on the map[93] that the origin might possibly be moved 10 degrees to the east. Dr. F. Omori located the origin of these earthquakes, making the latitude 60 degrees north, the longitude 140 degrees west.[94] Dr. R. D. Oldham[95] states that these shocks originated in latitude about 59° 5′ north and longitude 140° 0′ west. Field studies in 1905 and 1909 lead to the location of the earthquake origin in Yakutat Bay fiord. This is near latitude 59° 58′ 20″ north and longitude 139° 33′ 0″ west (see figure 5). This, of course, assumes a single origin and places it along an old fault-line associated with the 47½-foot uplift, the greatest observed change of level of the land in 1899. It seems correct for the great earthquake of September 10. The origins of the other earthquakes may have been slightly different and were perhaps not simple and single, but complex.

INTERVALS AND TIMES OF MAXIMA

From some of the best of the distant seismograph records Dr. R. D. Oldham has computed the intervals and compared them with the observed times of maxima of the three largest earthquakes.[96]

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[92] Nature, vol. lx, 1899, p. 545.

[93] Report of British Association for the Advancement of Science, 1900, pl. iii, opposite p. 77.

[94] Publications of Earthquake Investigation Committee in foreign languages, no. 5, pp. 61-65; no. 6, 1901, p. 51; no. 13, 1903, pp. 86-88.

[95] Quarterly Journal of the Geological Society, vol. lxii, 1906, p. 459.

[96] Unpublished manuscript. For a slightly different result with some of the same data, see Report of the British Association for the Advancement of Science, 1900, p. 77.

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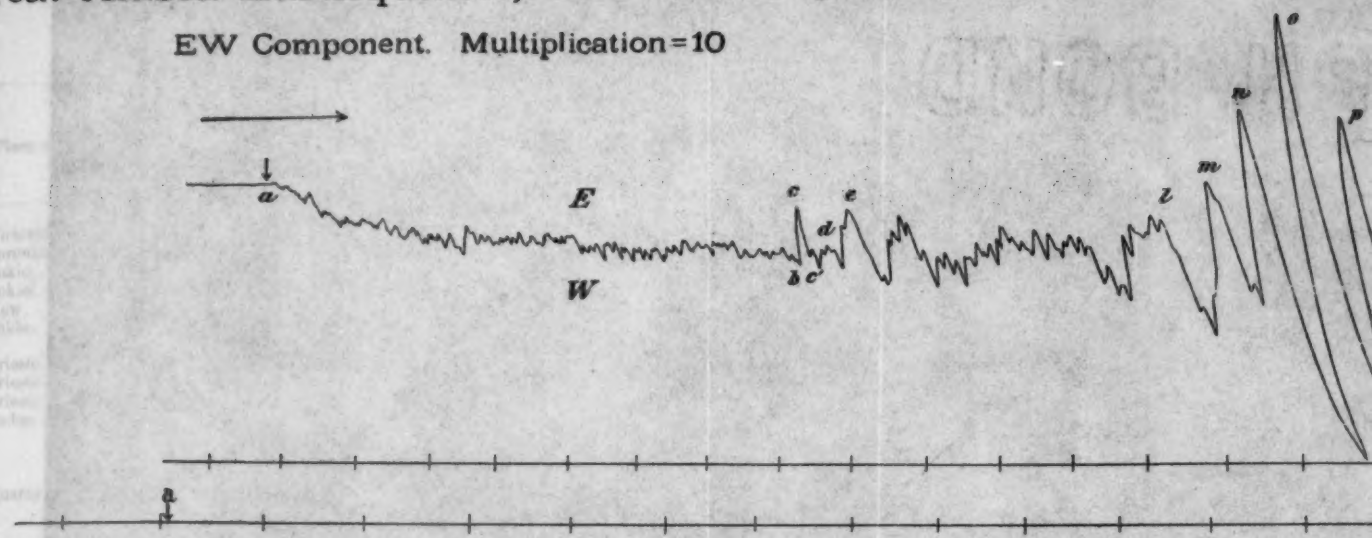
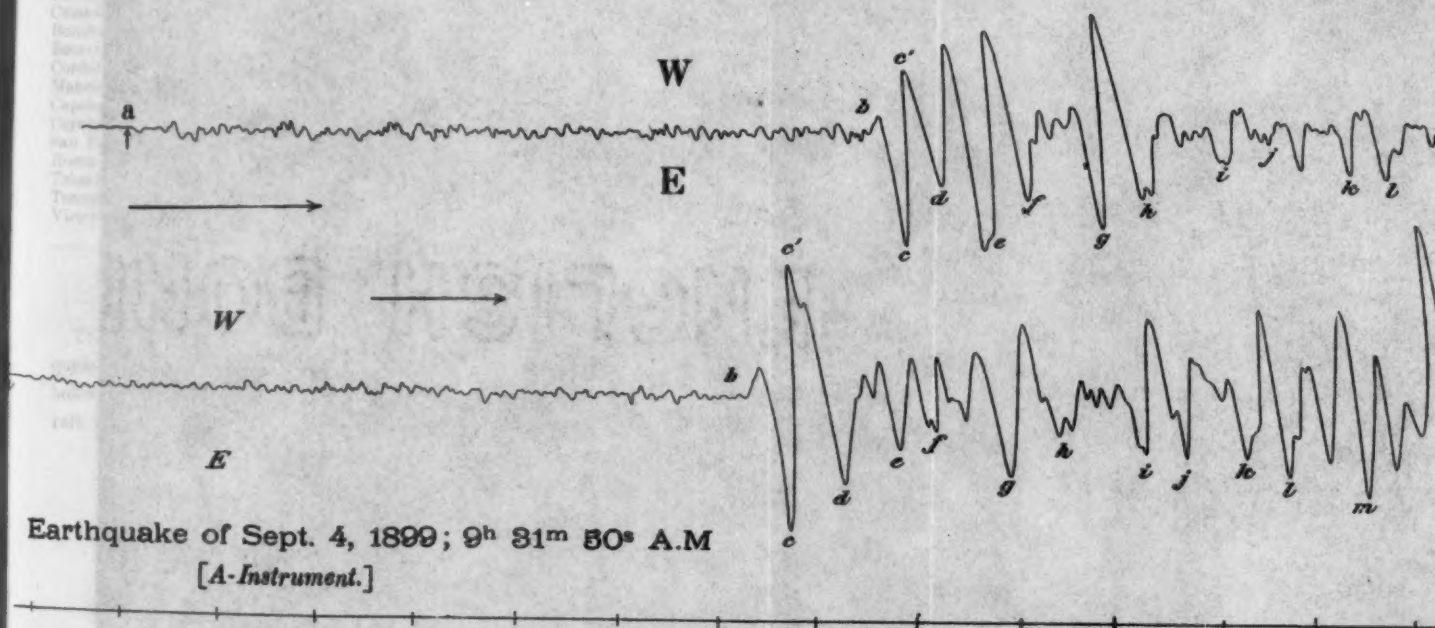
Great Alasca Earthquakes, Observed at Hongo, Tokyo.



Earthquake of Sept. 11, 1899; 6h 50m
[*A-Instrument.*]

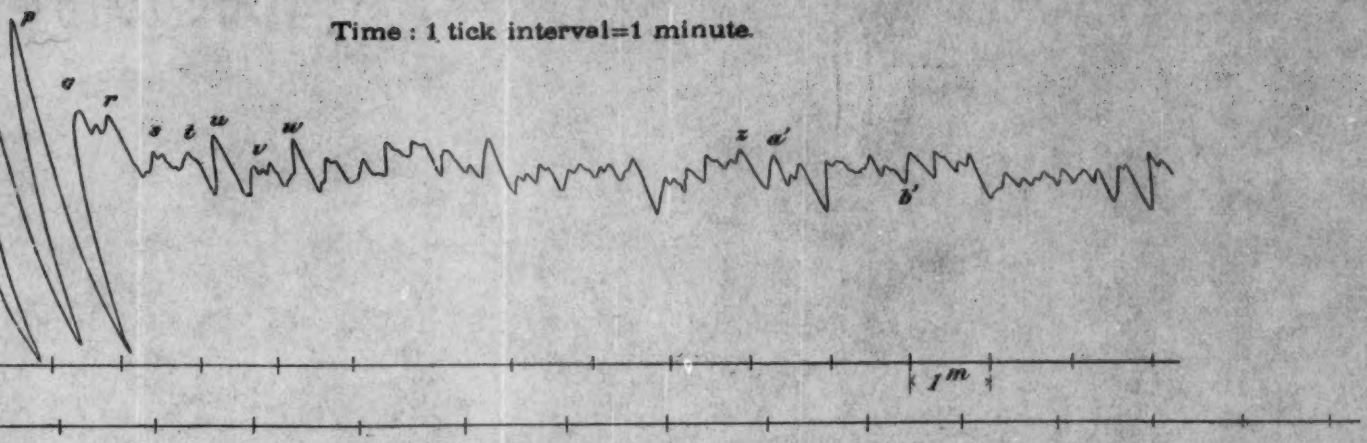


Earthquake of Sept. 4, 1899; 9h 31m 50s A.M
[*A-Instrument.*]

Earthquake of Oct. 9, 1900; 9h 37m 14s P.M.

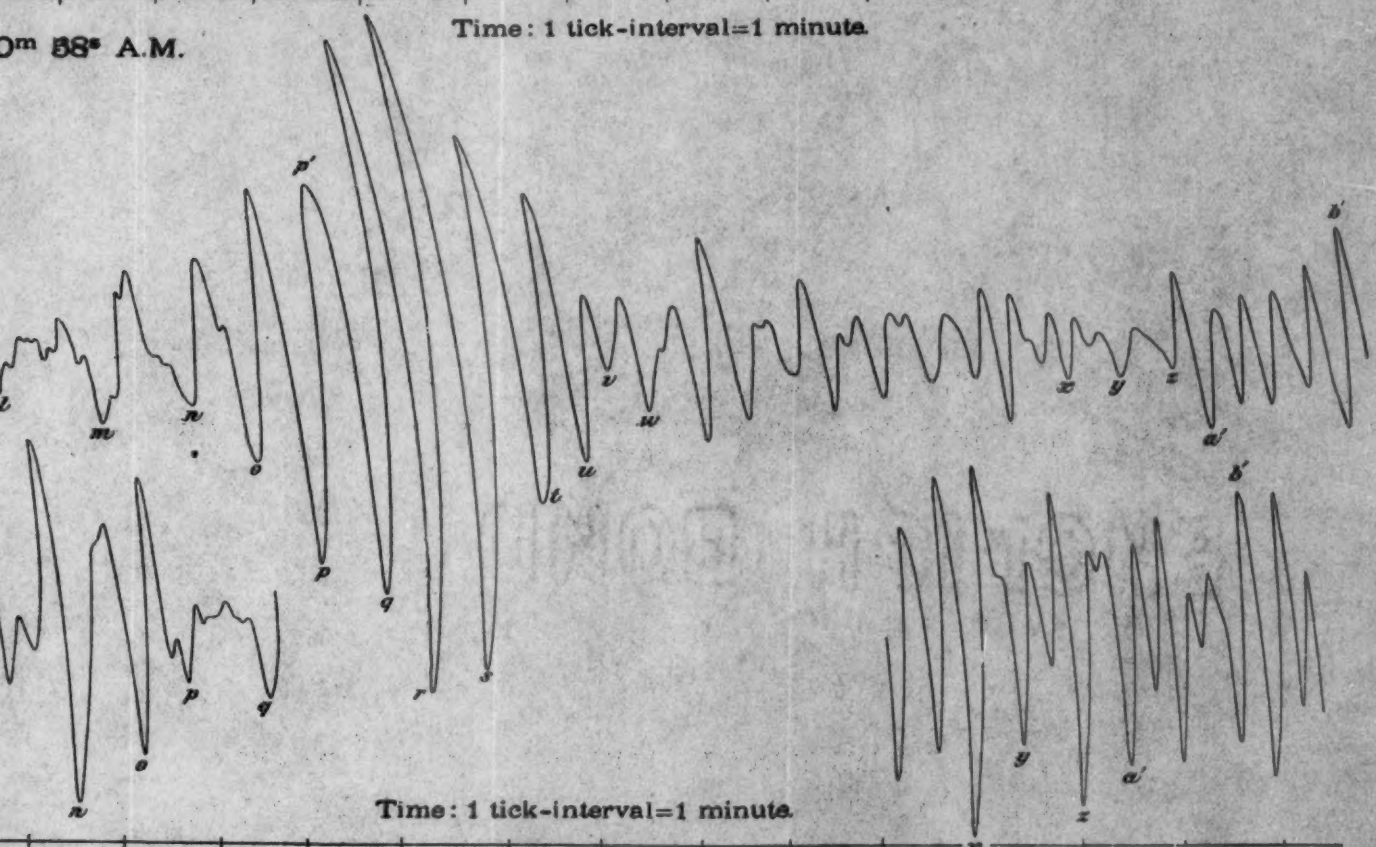
[*C-Instrument.*]

Time : 1 tick interval=1 minute.



Time : 1 tick-interval=1 minute.

0m 38s A.M.



Time : 1 tick-interval=1 minute.

Place of observation.	Distance from epicentra in degrees.	Calculated interval in minutes at 3 km. per second.	Recorded time of maxima in minutes after origin.		
			September 3.	September 10.	September 10.
Victoria	14.2	8.8	12.0	.....	.....
Toronto	39.0	24.2	23.5	23.8	23.6
Tokio	55.5	34.4	28.5	.....	29.5
Tokio	.....	.....	30.0	.....	.....
Kew	64.4	39.9	42 5	48.6	41.1
Shide	65.1	40.4	41.0	46.3	44.0
			41.2	.....	.....
Trieste	73.0	45.3	68.4	54.0	48.5
Trieste	.....	45.3	71.0	48.6	46.4
Trieste	.....	45.3	51.0	46.3	46.9
Padua	73.1	45.4	54.5	50 5	47.5
		45.4	60.5	55.5	46.5
		45.4	54.5	50.0	45.5
		45.4	60.5	.....	47.5
Quarto	74.3	46.1	49.5	47.5	46.2
		46.1	48.5	.....	60.5
		46.1	48.5	.....	.....
Rome	76.5	47.4	.....	53.8	42.5
Rocca di Papa	.....	.....	.....	51.5	44.5
			47.5	54.1	46.3
			65.1	54.1	45.3
			52.5	48.7	.....
			51.3	.....	.....
			52.7	.....	.....
San Fernando	76.8	47.6	56.5	48.2	45.4
Ischia	77.7	48.2	52.5	.....	55.5
Ischia	.....	.....	66.0	.....	.....
Catania	81.3	50.7	53.1	52.8	49 1
Catania	.....	.....	54.1	58.8	56.1
Bombay	95.5	60 6	58.0	57.3	58.6
Batavia	107.5	66.6	.....	71.7	76.8
Cordoba	109.3	67.8	.....	69.3	83.3
Mauritius	138.0	85.6	91.0	.....	87.7
Capetown	149.6	92.8	91.0	90.5	84.7
Capetown	210 4	.....	111.5	107.5	102.0
San Fernando	283.2	.....	169.0	.....	.....
Rocca di Papa	283.5	.....	169.5	.....	.....
Trieste	.....	.....	.....	131.5	.....
Toronto	321.0	.....	214.5	.....	194.5
Victoria	345.8	.....	219.5	.....	.....

SEISMOGRAPH RECORD COMPARED WITH LOCAL ACCOUNTS

The most reliable of the local accounts show that the principal earthquakes felt in Alaska came on the following dates and at hours listed below. The origin in most cases was near Yakutat, but the nearest accurate time record was usually at Cape Whitshed.

Date.	Yakutat Village,[a] latitude 59° 33′ north, longitude 139° 45′ west.	Cape Whitshed,[b] latitude 60° 27′ 34″ north, longitude 145° 54′ 35″ west.
September 3	P. M. (*)	P. M. 2h. 40m.
After-shocks		3h. 22m. 30s. (*) 6h. 45m. 7h. 10m. 7h. 44m.
September 10[c]	A. M. 7h. 40m.	A. M. 7h. 43m.
After-shocks		8h. 1m. 10h. 38m. 34s. 10h. 53m. 45s. 10h. 59m. 55s. 11h. 5m. 5s.
September 10[d]	P. M. 12h. 15m.	A. M. 11h. 58m. 33s.
After-shocks		P. M. 12h. 7m. 8s. 5h. 36m. 8s. 5h. 44m. 2s. 5h. 51m. 41s.
September 15[e]	P. M. 7h. 15m. 7h. 30m.	
September 17[f]		
September 23		A. M. 1h. 22m.
After-shocks		1h. 28m. 9s. 1h. 33m. 9s. 1h. 40m. 9s. 1h. 41m. 51s.
September 26		A. M. 2h. 49m. P. M. 12h. 5m. 38s. 2h. 46m.
September 29		During night.

a Observed at Yakutat Village by R. W. Beasley. Irregularly regulated "sun time" of local meridian.

b Observed in Coast Survey camp by H. P. Ritter, with good and well rated chronometer, using solar time of local meridian.

(*) No time record.

c The early shock.

d The great earthquake.

e Not recorded at Cape Whitshed. Shocks were felt between September 12 and 16, but not precisely recorded because of general uproar of storm then raging. This September 15th shock was felt with great intensity at Yakutat, as well as at Skagway.

f If observed at Yakutat or Cape Whitshed the shock was not recorded. Indefinite statement of observation at Skagway and Juneau.

No time record is available for the possible initial shock on August 27, 1899, but there seems to have been no great shock recorded by seismographs that day. All the seismograph records, so far as known to the writer, show world-shaking earthquakes on September 3, twice on September 10 and September 23 at most of the observatories where instruments were then installed (figure 8).

There seems to have been no seismograph record of the September 15th shock, although reported as severe at Yakutat, Skagway, etcetera.

The September 17th shock, though widely recorded by seismographs, was not felt at Yakutat or Cape Whitshed. Its observation at Skagway and Juneau is indefinite. Professor Milne has computed, however, that this shock was in Alaska.[97] Its origin was probably not in Yakutat Bay.

The shock of September 23 was recorded throughout the world, the record having an amplitude of 17 millimeters at Victoria and then going clear off the paper.

The shock of September 26 was recorded throughout the world, but was less violent than that of the 23d. Its amplitude was 7.4 millimeters at Victoria and 4.1 millimeters at Toronto.

The shock of September 29, the final one of the series, happens to coincide in date with the Ceram earthquake in the East Indies. The Victoria seismogram, with an amplitude of 2.5 millimeters, might possibly belong to the Alaskan series, but the exact time of the shock felt in the night at Cape Whitshed is not available for determining this conclusively.

TABLES OF SEISMOGRAPHIC DATA

The following three tables include some of the available data showing the orderly and progressive time, duration, and intensity as the tremors

[97] Nature, vol. lx, 1899, p. 545.

of the three largest earthquakes originating at Yakutat moved outward through the earth's crust and interior. The figures selected are taken chiefly from circulars 1 and 2 of the Seismological Committee of the British Association for the Advancement of Science. All records are from Milne horizontal pendulums of the same general type, recording is uniformly done, the magnification of amplitude is the same, and observations may, therefore, be roughly compared. All observations are reduced to Greenwich mean time.

The places of observation are shown in figure 8. The observed times at the Alaskan localities are placed for convenience in the first column, although not seismographic and not exactly equivalent to the commencement of the preliminary tremors. It is recognized that the recorded maxima on seismographs with little damping are largely instrumental and do not correspond to the greatest movement of the earth. It should be stated that these are based on old calculations, and that trained seismologists might now determine the times and occurrences of the various shocks with greater accuracy, in view of the most recent seismological studies. The main facts, however, are briefly assembled here for convenience of reference.

Shock of September 3–4, 1899

Place of observation.	Commencement of preliminary tremors.	Maximum.	Amplitude in millimeters or seconds of arc.	Total duration.
	h. m. s.	h. m. s.		h. m. s.
Yakutat (Disenchantment) Bay, Alaska.	0 21 40*	.....	.....	.....
Cape Whitshed, Alaska.	0 23 38	.....	.....	.....
Victoria, British Columbia.	0 26 13	0 35 9	Off paper.....	.....
Toronto, Canada.....	0 30 14	0 48 19	24 millimeters.....	7 54 19
Tokio, Japan.....	0 30 65[a]	.....	1.35 millimeters[b] ..	1 17
Kew, England	0 33.6	1 3.0[b]	7.49 inches.....	2 49.2
Shide, England.....	0 35.0*	1 1.5	15.0 millimeters[f] ..	.....
San Fernando, Spain.	0 33.6	1 7.1	8.17 inches.....	3 19.9
Bombay (Colaba), India.	0 45 25	1 18 34	4.66 inches.....	.....
Cordoba, Argentina..	0 40.8*	1 52.4	6.5 millimeters	3 14.6
Mauritius, Indian Ocean.	.....	1 51.5[g]	5.70 inches.....	.....
Capetown, South Africa.	0 46.2	1 51.5[d]	2.5 inches.....	.....

* Computed by Dr. R. D. Oldham from seismograph records as 0h. 20m. 30s.

a 0h. 31m. 52s.

b First maximum, 1h. 3.0m.
Second maximum, 1h. 7.3m.

c Or 23h. 49.1m.

d Or 2h. 0.9m., or 2h. 12.0m. times. Recorded roughly on account of failure of occultation watch.

e Given as 20h. 40.8, September 4, probably error for 0h. 40.8m.

f Boom caught at maximum by eclipse plate of watch.

g Beginning and end lost in air tremors.

h Amplitude of principal portion given elsewhere as 15.2 millimeters.

Early Shock of September 10, 1899

Place of observations.	Commencement of preliminary tremors.	Maximum.	Amplitude in millimeters or seconds of arc.	Total duration.
	h. m. s.	h. m. s.		h. m.
Yakutat (Disenchantment) Bay, Alaska.	17 01. 30 *	.....	.....	.....
Cape Whitshed, Alaska.....	(a)	.....	.....	.....
Victoria, British Columbia..	Lost in mails.	.....	Vibrations across paper.	.....
Toronto, Canada.....	17 11 56	17 25 19	.....	.....
Kew, England.....	17 15.3	17 50.1 b	2.18 inches exceeded.	1 39
Shide, England	.....	17 48.0	.....	2 12.2
San Fernando, Spain.....	17 9.9	17 47.1	2.58 inches..	.....
Bombay (Colaba), India....	.....	17 58 47	0.78 inch....	.....
Madras, India.....	17 28.3	18 { 3.2 c / 12.5	1.0 / 0.7 }	.....
Batavia, Java.....	17 30.2	18 8.2	2.0 inches...	1 16
Cordoba, Argentina.....	17 32 8	18 10.8	2.0 mm.	2 12
Cape Town, South Africa...	17 36.2	18 { 32.1 / 34.6	{ 0.5inch	2 0

a The time of origin given above for Disenchantment Bay was computed by Dr. R. D. Oldham from seismograph records.

b First maximum, 17h. 50.1m.
Second maximum, 17h. 53.5m.

c Clock stopped at 18h. 36m.

The great Earthquake of September 10, 1899

Place of observation.	Commencement of preliminary tremors.	Maximum.	Amplitude in millimeters or seconds of arc.	Total duration.
	h. m. s.	h. m. s.		h. m. s.
Yakutat (Disenchantment) Bay.	21 40 13[a]	.....	.....	.....
Cape Whitshed, Alaska.	21 42 11	.....	.....	.....
Atlin, British Columbia.	21 39 20	.....	.....	.....
Eagle, Alaska.....	21 40	.....	.....	.....
Victoria, British Columbia.	"Splendid seismogram lost in the mails."		"Over an inch."	
Toronto, Canada.....	20 42 14	22 3 6	Vibrations across paper.	5 36 55
Kew, England.....	21 1.6	22 20.21[b]	10.8 inches.....	3 0
Shide, England.....	21 23.0	22 23.5	.....	.....
San Fernando, Spain..	21 3.9	22 24.9	14.62 inches.....	4 11.8
Bombay (Colaba), India.	....	22 38 9	1.78 inches.....	.....
Batavia, Java.	22 0.0	22 56.3	9.3 inches	2 11
Cordoba, Argentina...	21 56.8	23 2.8	5 millimeters	.....
Mauritius, Indian Ocean.[c]	.....	23 { 7.2 / 15.0	1.47 inches..... / 1 44 inches.....	..... / .....
Capetown, South Africa.	22 1 4	23 { 0.4 / 4 2 / 9.1 / 13.3 / 21.5 }	2.4 inches	3 30

[a] The apparent anomaly of the shock being felt at Toronto, etcetera, before it was recorded at the origin is probably due to the fact that the extremely delicate first movements which separate into the preliminary tremors were well started on the way before the more severe motion, perceptible to the senses of persons nearer the origin, was recorded. Doctor Oldham computes this same origin as 21h. 39m. 30s.

[b] First maximum, 22h. 20.21m.
Second maximum, 22h. 25.6m.

[c] Air tremors marked beginning and end.

MAGNETOGRAPH RECORDS

Instruments for the measurement of terrestrial magnetism also recorded the Yakutat Bay earthquakes. The optical registration and the accurate time observation make these valuable as earthquake records. So far as reported, the magnetographs recorded these shocks at Toronto, Canada;[98] Utrecht, Holland, and Wilhelmshaven, Germany, but not at

[98] Fifth Report of the Seismological Committee of the British Association for the Advancement of Science, 1900, p. 83.

Greenwich or Falmouth, England; Parc St. Maur, Paris, and Perpignan, France; Copenhagen, Denmark, or Manila, Philippine Islands.

PLACES OF INSTRUMENTAL RECORDS

Beside the places listed in the tables above, the Yakutat Bay earthquakes were recorded at many other observatories. The following list of places of observations has been compiled to show the world-shaking

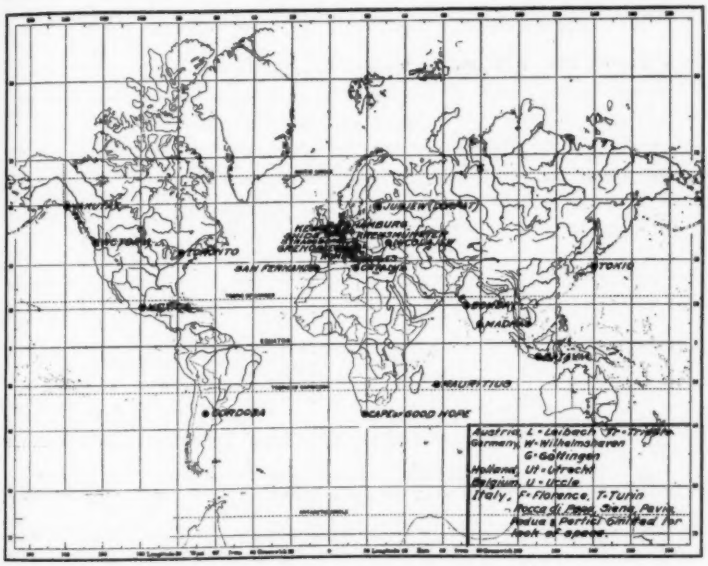


FIGURE 8.—*Map showing Seismograph Stations*

Yakutat, Alaska, and seismograph stations throughout the world at which the earthquakes of September, 1899, were recorded

character of the principal shocks. It is also partly bibliographic. The location of these places is shown in figure 8. Many of the instrumental records are from circulars 1 and 2 of the Seismological Committee of the British Association for the Advancement of Science (Prof. J. W. Judd, chairman; Mr. John Milne, secretary). Some of the others refer to unpublished materials furnished for the U. S. Geological Survey Professional Paper dealing with these earthquakes, by R. S. Tarr and the writer.

North America

Place.	Type of seismograph.	Described by	Published in
Victoria, British Columbia.	Milne.....	Seismological Committee.	Circular 2, B. A. A. S., 1900, pp. 38–39.
Toronto, Ontario	Milne.....	Seismological Committee.	Circular 2, B. A. A. S., 1900, pp. 36–37.
Toronto (Agincourt), Ontario.	(Magnetograph).	R. F. Stupart.	Personal communication.
		J. Milne	B. A. A. S., 5th Report Seismological Committee, 1900, p. 83.
City of Mexico, Mexico.	Milne.....	.....	.....

South America

Cordoba, Argentina..	Milne.....	Seismological Committee.	Circular 2, B. A. A. S., 1900, pp. 50–51.

Europe

Shide, Isle of Wight.	Milne.....	John Milne..	Circular 1, B. A. A. S., 1900, p. 3.
Kew, England	Milne.....	Seismological Committee.	Circular 1, B. A. A. S., 1900, pp. 6–7, 9.
Uccle, Belgium.....	Rebeur-Ehlert ..	E. Lagrange..	Bull. Soc. Belge d'Astron. 5me Année, 1901, No. 2, p. 4.
Utrecht (de Bilt), Holland.	(Magnetograph)	G. van Dyk ..	Personal communication.
Hamburg, Germany.	Rebeur-Ehlert ..	R. Schült.....	Personal communication.
Wilhelmshaven, Germany.	(Magnetograph).	H. Capelle...	Personal communication.
Göttingen, Germany.	.....	L. Geiger.....	Personal communication.
Strassburg, Germany.	Rebeur-Ehlert ..	A. Rudolph..	Personal communication.
		J. P. van der Stok.	Konink. Akad. Wetens. te Amsterdam, vol. ii, 1900, pp. 244–246.
Grenoble, France....	....	Paul Reboul..	Personal communication.
San Fernando, Spain.	Milne.....	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 64.
Rome (Rocca di Papa), Italy.	Agamennone and Vicentini vertical pendula and two horizontal pendula.	G. Agamennone.	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp 178–182, 194–196, 199–202, 224.
Catania, Italy	....	A. Riccó	Boll. Soc. Sism Ital., vol. vi, 1900–1901, pp. 186–187, 197, 204–205, 225.
Naples (Casamicciola), Italy.	Six instruments.	G. Grablovitz.	Boll. Soc. Sism Ital., vol. vi, 1900–1901, pp. 183–186, 202–204, 224–225.
Naples (Portici), Italy.	....	.....	....

Europe—Continued

Place.	Type of seismograph.	Described by	Published in
Rome, Italy		S. S. del Coll. Rom.	Boll. Soc. Sism Ital., vol. vi, 1900–1901, pp. 182–183, 194, 199, 223.
Florence (Quarto Castello), Italy.	Vicentini and others.	A. Bastogi, D. R. Stiattesi.	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 187–189, 197–198, 205–207, 225–226.
Padua, Italy			
Pavia, Italy		E. Oddone	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 189, 198, 207, 226–227.
Siena, Italy	Vicentini		Boll. Soc. Sism. Ital., vol. vi, 1900–1901, p. 205.
Turin, Italy		R. Osserv. Astron.	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 189–190, 207–208.
Trieste, Austria	Rebeur-Ehlert	E. Mazelle	Mitt. d. Erdb. Komm. d. kais. Akad. Wiss. in Wien, Bd. cix, 1900, pp. 28–31, 34–35.
Kremsmünster, Austria.		P. F. Schwab.	Mitt. d. Erdb. Komm. d. kais. Akad. Wiss. in Wien, xv, 1900, pp. 42–45.
Laibach, Austria	Vicentini	A. Belar	Boll. Soc. Sism. Ital., vol. vi, 1900–1901, pp. 190, 208, 227.
Nicolajew, Russia		J. Kortazzi	Beiträge Z. Geophysik, vol. iv, 1900, pp. 404–405.
Jurjew (Dorpat), Russia.	Zollner-Repsold, Rebeur-Paschwitz.	G. Lewitzky.	Personal communication.

Asia

Tokio (Hongo), Japan.	Omori	F. Omori	Pubs. E. I. C. (foreign languages), No. 6, 1901, pp. 48–51.
Tokio (Hitotsubashi), Japan.	Omori	F. Omori	Pubs. E. I. C. (foreign languages), No. 13, 1903, pp. 96–99; No. 21, 1905, pp. 46–49.
Tokio, Japan	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, pp. 24–25.
Batavia, Java	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 20.
		R. D. M. Verbeek.	Konink. Magn. en Met. Obs., Batavia, vol. xxii, 1899, part i.
Bombay (Colaba), India.	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 13.
Madras, India	Milne	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 12.

Africa

Place.	Type of seismograph.	Described by	Published in
Mauritius, Indian Ocean.	Milne.....	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 17.
Cape Town, South Africa.	Milne.....	Seismological Committee.	Circular 1, B. A. A. S., 1900, p. 22.

Times of Yakutat Bay Earthquakes

Determined from seismograms

Dr. D. W. Oldham has computed the time of origin of the three largest Yakutat Bay earthquakes[99] from the distant seismograph records. These times he determined, with an error of not more than one minute of time, by the use of curves first produced in his paper, "The propagation of earthquake motion to great distances."[100]

In a personal communication, which he has kindly allowed me to use, he states that in this computation he used

"the records of the Italian seismographs and adopted this course for two reasons; that, as shown in the paper referred to, the heavily weighted pendula with mechanical record give much more concordant results for the first two phases than light pendula with a slow-moving photographic record, and, 2d, because the curves having been deduced from the records of instruments of the type used in Italy, it is logical to use the data obtained from instruments of this type in applying them to obtain the time of origin of an earthquake.

"In the case of the Alaskan earthquakes the Italian observatories are distant from 73 degrees, in the case of Padua, to 81 degrees in the case of Catania. The mean time interval, as deduced from the curves, is consequently about 13.5 minutes for the first and 23.5 minutes for the second phase. I have consequently extracted from the published accounts the times of commencement, and, where recorded, of the first marked increase of movement, representing the second phase; these are tabulated below and the resulting time of origin deduced. The times so obtained are doubtless subject to a slight error, but this probably does not exceed one minute of time—an error which becomes insignificant when dealing with the comparatively slow traveling waves of the third phase. (The times tabulated here have been obtained, in the case of Padua, directly from the diagrams obtained there, which Professor Vicentini very kindly allowed me to examine; in the case of the observatory at Quarto (Florence), from the publications of that observatory, and in the case of the other Italian observatories, from the details published in part II of the Bollettino della Societa Sismologica Italiana.)

[99] Quarterly Journal of the Geological Society, vol. lxii, 1906, p. 459.

[100] Philosophical Transactions of the Royal Society of London, series A, vol. 194, 1900, pp. 35-74.

Earthquake of September 4, 1899—Shide No. 333

Distance.	Place.	First phase.		Second phase.	
Degrees.		*h.*	*m.*	*h.*	*m.*
73.1	Padua	0	34.3	0	44
		0	34.3	0	45
		0	34.3		
74.3	Quarto	0	33.8		
		0	33.8		
		0	34.5		
		0	33.8		
		0	33.8		
76.5	Rome	0	34.6	0	46.5
		0	34 7		
76.5	Rocca	0	33.3	0	43.6
		0	35.5		
		0	34.5	0	45.0
		0	34.6		
		0	34.25		
77.7	Ischia	0	34.5	0	44.5
		0	34.5	0	44.5
		0	34.6	0	44.5
		0	34.5	0	44.3
		0	34.5	0	44.3
		0	34.7	0	44.3
		0	34.6	0	45.5
		0	34.6	0	44.4
81.3	Catania	0	34.7	0	45.7

"The mean time for the first phase may be taken as about 0h. 34m., and for the second phase as about 0h. 44m., giving the time of origin as 0h. 20.5m., Greenwich mean time.

Earthquake of September 10, 1899—Shide No. 337

Distance.	Place.	First phase.		Second phase.	
Degrees.		*h.*	*m.*	*h.*	*m.*
73.1	Padua	17	15.1	17	24.7
		17	15.2		
		17	15.1		
74.3	Quarto	17	15.0	17	24.5
		17	14.7		
		17	14.7		
76.5	Rome	17	15.6	17	25.8
76.5	Rocca	17	15.2	17	25.0
				17	25.1
77.7	Ischia	17	15.7	17	25.6
81.3	Catania	17	15.3	17	25.0

"The mean time for the first phase is 17h. 15m. and for the second phase 17h. 25m., giving 17h. 1.5m., Greenwich mean time, as the time of origin.

Earthquake of September 10, 1899—Shide No. 338

Distance.	Place.	First phase.		Second phase.	
Degrees.		*h.*	*m.*	*h.*	*m.*
73.1	Padua	21	53.1	22	2.7
			53.1	22	2.3
			53.0		
74.3	Quarto			22	9.8(?)
				22	9.8(?)
				22	2.7
76.5	Rome	21	50.5		
76.5	Rocca			22	3.2
		21	53.4	22	3.6
		21	53.4	22	3.4
77.7	Ischia	21	53.5	22	3.5
81.3	Catania	21	52.9	22	1.0

"The resulting mean time for the first phase is about 21h. 53m., and for the second phase 22h. 3m., which give a corrected time of 21h. 39.5m., Greenwich mean time, as the time of origin."

ALASKAN TIME RECORDS

The time records from Alaska which it is safe to use are from only three localities (figure 4). This is because (*a*) there were only a few persons in this wilderness area in September, 1899; (*b*) only a few of these persons observed the times of the earthquake shocks accurately, and (*c*) the timepieces of the few reliable observers were imperfect, the exact position was not known, or the timepiece was not afterwards corrected to given mean time of the local meridian.

The first of the three most reliable time records comes from Mr. H. P. Ritter, assistant, U. S. Coast and Geodetic Survey, who was at Cape Whitshed, Alaska, 220 miles west of Yakutat. His readings were taken with a good and well rated chronometer, giving mean local time of a point whose exact latitude and longitude had been determined. The second records were made by Judge W. G. Myers, local observer, U. S. Weather Bureau, at Eagle, Alaska, 340 miles north of Yakutat. His record is based upon local solar time. The third observations are by Prof. J. C. Gwillim, of the Geological Survey of Canada, who was near Atlin Lake, British Columbia, about 220 miles east of Yakutat. He had determined his position and set his watch to solar time only 45 minutes before one of the earthquakes.

Other records, not quite so accurate, are by R. W. Beasley, at Yakutat; Lieut. W. C. Babcock, of the U. S. Army, in the Chugach Mountains; Messrs. Brooks and Peters, of the U. S. Geological Survey, on the Tanana

River; Messrs. Schrader, Gerdine, and Witherspoon, of the U. S. Geological Survey, on the Koyukuk River, and others. These last three parties were engaged in topographic work, and their records might possibly be adjusted. The time observations at Skagway and other points on the telegraph line should also be fairly correct.

The times of origin in inner Yakutat Bay (Disenchantment Bay) have been determined as follows: The first earthquake on September 3 was recorded at Cape Whitshed,[101] the Coast Survey camp near the Copper River delta, at 2.40 p. m. Allowing a correction of 25 minutes and 26 3-10 seconds of time for 6 degrees 21 minutes and 35 seconds of longitude and a correction of 1 minute and 58 seconds of time for transmission about 220 miles, at the arbitrary rate of 3 kilometers, or a little over two miles per second,[102] we determine the time of origin of the shock of Disenchantment Bay as about 3.03½ p. m. September 3 (3h. 3m. 28⅓s., local time at Yukatat, or 0h. 21m. 40⅓s. a. m., September 4, when reduced to Greenwich mean time).

The first shock recorded on September 10 at Camp Whitshed came at 7.43 a. m. When this is corrected for longitude and transmission as above, it is found that it would have been felt at Disenchantment Bay at 8.06½ a. m. (8h. 6m. 28⅓s., local time at Yakutat, or 17h. 24m. 40⅓s., September 10, in Greenwich meridian time). This is about 23 minutes later than the shock shown by the seismograph records should have originated, and forces us to conclude that either (*a*) the first shaking at the Coast Survey camp was mild and not recorded, because coming just at or near the time of rising, or (*b*) that this shock was not central in Disenchantment Bay, but originated somewhere else in the mountains near by. The intensity of the first shock felt in the prospector's camp in Disenchantment Bay is against this hypothesis, and the time record by R. W. Beasley at Yakutat Village (7.40 a. m.) indicates the former to have been the case. Mr. Beasley's sun time, though close, is not precise enough, and we have adopted Doctor Oldham's seismograph time record for the origin of this shock, as is shown on a subsequent page.

A similar correction for longitude and transmission fixes the time of origin of the heaviest shock on September 10, which was recorded at the Coast Survey camp at 11h. 58m. 33s. as about 12.22 p. m. (12h. 22m. 1s.) local time in Disenchantment Bay, or 21h. 40m. 13s. when reduced to Greenwich mean time.

The September 15th earthquake, observed at Yakutat at 7.15 a. m.

[101] Camp Whitshed, longitude 145° 54′ 35″ west, latitude 60° 27′ 34″ north; Disenchantment Bay, longitude 139° 33′ 0″ west, latitude 59° 58′ 20″ north.

[102] This may have been as great as 7 or 8 kilometers per second.

(not recorded at Cape Whitshed), originated at 7h. 15m., local time, at Yakutat, or 16h. 33m. 12s., Greenwich mean time.

The September 23d earthquake, observed at Cape Whitshed at 1h. 22m. a. m., originated at Yakutat at 1h. 45m. 28s., or 11h. 3m. 40s., Greenwich mean time.

The September 26th earthquake, observed at Cape Whitshed at 2h. 49m. a. m., originated at Yakutat at 3h. 12m. 30s., or 12h. 40m. 42s., Greenwich mean time.

THE CORRECTED TIMES OF ORIGIN

Date.	Time at Yakutat Bay.				Same in Greenwich mean time.			
	h.	m.	s.		h.	m.	s.	
September 3....	3	3	28	p. m.....	0	21	40	(September 4.)
September 10....	7	43	18	a. m.....	17	1	30	
September 10....	12	22	1	p. m.....	21	40	13	
September 15....	7	15		a. m.....	16	33	12	
September 17....								
September 23 ...	1	45	28	a. m.....	11	3	40	
September 26 ...	3	12	30	a. m.....	12	40	42	
September 29....								

COMPARISON OF LOCAL TIME RECORDS AND SEISMOGRAPHIC TIME RECORDS

A comparison of the local time records just quoted with those worked out by Doctor Oldham (page 386) from the seismograph records follows, showing the times of origin determined for inner Yakutat or Disenchantment Bay for the three chief shocks. All are given in Greenwich and in local time.

September 3d Earthquake

P. M. A. M., Sept. 4.

Local record.—3h. 3m. 28s., local solar time; or 0h. 21m. 40s., Greenwich mean time.

Seismograph record.—3h. 2m. 18s., local solar time; or 0h. 20m. 30s., Greenwich mean time.

September 10th Earthquake (the early shock)

A. M.

Local record.—7h. 40m. 0s., local solar time; or 16h. 58m. 12s., Greenwich mean time.

Seismograph record.—7h. 43m. 18s., local solar time; or 17h. 1m. 30s. Greenwich mean time.

September 10th Earthquake (the great Earthquake)

P. M.

Local record.—12h. 22m. 1s., local solar time; or 21h. 40m. 13s., Greenwich mean time.

Seismograph record.—12h. 21m. 18s., local solar time; or 21h. 39m. 30s., Greenwich mean time.

A comparison of these three sets of records shows a close agreement in two out of the three. In the case of the heavy final shock of September 10 the agreement is within 43 seconds, and in the case of the September 3d shock the determinations check within 70 seconds, coming very close to the possible error of "one minute of time" which Doctor Oldham allows himself (page 386). So close a determination must be a source of gratification to Doctor Oldham, as this was probably the first attempt ever made to determine times of origin from distant seismograph records.

The agreement of the two sets of records also accords well with the assumption that the chief shocks on September 3, September 10 and 23 had their principal origins in or near Yakutat Bay. It should be remembered, however, that the rate of transmission assumed, 3 kilometers per second, on which the local time records are based, is wholly arbitrary. The most recent studies of velocity of propagation suggest that a rate of 7 or 8 kilometers per second may have been attained.

SPEED OF TRANSMISSION

An attempt to check the determination of rate of transmission by comparison with the only other local time records of any accuracy, Professor Gwillim's observation near Atlin on September 10, a place almost exactly as far east of Disenchantment Bay as Cape Whitshed is west of there, and Judge Myers' observation at Eagle, about 340 miles north-northwest of Disenchantment Bay, results as follows:

Time of observation, 12h. 45m. 0s. p. m., local solar time near Atlin; latitude of place of observation, near Atlin, 59° 24′ 30″ north; longitude, 133° 35′ 0″ west; latitude of Disenchantment Bay, 59° 58′ 20″ north; longitude, 139° 33′ 0″ west). Correcting this observation for a difference of 23 minutes and 52 seconds of time with 5° 58′ of longitude, we find that the shock appears to have been felt by Professor Gwillim at 12h. 21m. 8s. (Yakutat Bay time), or 53 seconds before it originated at Yakutat.

Similarly a correction of the supposed accurate local solar time observation at Eagle (latitude 64° 13′ north; longitude 141° 15′ west), where the earthquake was felt in the Weather Bureau observatory at 12h. 15m. p. m., results as follows: A correction of 6m. 48s. of time for 1° 42′ of longitude shows that the shock was felt by Judge Myers at 12h. 21m. 48s. (Yakutat Bay time), or apparently 13 seconds before it was generated at Yakutat.

It might be either that (*a*) the time of origin given by us for Yakutat Bay is a minute, more or less, too late, as it would be if we assumed too fast a rate of transmission from Yakutat to the Coast Survey camp at

Cape Whitshed; or (*b*) the determinations of local time by Professor Gwillim and Judge Myers are in slight error, and in each case the observed time comes, suspiciously, on an even five minutes; or (*c*) the chronometer at the Coast Survey camp was not exactly right; or (*d*) there may have been a complex of synchronous origins at other places in the mountains beside Disenchantment Bay. One of the first two explanations is believed to account for the discrepancies. The whole matter is stated thus fully in order to show the futility of any attempt at closer computations based upon the local records at hand.

The speed of transmission for a longer distance, Yakutat Bay to Victoria, British Columbia, is as follows, taking the data from the shock of September 3: Disenchantment Bay, latitude 59° 58′ 20″ north; longitude 139° 33′ west; Victoria, latitude 48° 23′ north; longitude 123° 19′ west. Distance in miles along surface (computed from an 18-inch globe), about 1,000 miles. Time at origin, 0h. 21m. 40s., Greenwich mean time; time at Victoria, 0h. 35m. 9s., Greenwich mean time. Interval for transmission, 13 minutes and 29 seconds, or 809 seconds; 1,000 miles in 809 seconds gives a speed of 1.23 miles, or 2.1 kilometers, per second.

The rate at which the earthquake tremors moved for greater distances is shown in the following table, which is based upon computations by Prof. John Milne[103] on the assumption of an origin in the ocean west of Yakutat, and therefore subject to a slight error.

Speed of large Waves of Three of the Yakutat Bay Earthquakes, in Kilometers per Second.

From Milne's assumed origin, southwest of Yakutat to—	September 3 (Shide No. 333).	September 10 (Shide No. 337), early shock.	September 10 (Shide No. 338), the great earthquake.
Victoria			
Toronto	3.4		
Mexico		2.3	2.7
Shide	3.2	2.7	2.9
San Fernando	3.1	3.1	3.1
Bombay	3.6	3.6	3.4
Batavia		2.9	2.3
Cape Town	3.4	3.5	3.7
Average speed	3.3	3.0	3.0

Average speed of all 17 observations, with origin assumed by Professor Milne, 3.1 kilometers, or almost 2 miles per second.

[103] Fifth Report on Seismological Investigations of the British Association for the Advancement of Science, 1900, plate iii, opposite p. 77.

Professor Milne has also shown that the time necessary for one of these shocks (September 3) to traverse the earth's circumference or two diameters slightly exceeds 210 minutes.[104] This is a rate of about 1.9 miles, or 3.0 kilometers, per second. Doctor Omori made a similar calculation for the September 10th waves,[105] which traveled around the earth with a velocity of 3.6 kilometers per second.

Prof. C. G. Knott[106] has analyzed the relationship of speed of transmission to the location of the paths of the three chief Yakutat Bay earthquakes as follows, on the assumption that the path is not along the chord, but more approximately along the arc. The paths lie as follows:

Victoria..... Under sea.
Toronto.....Half sea, half land.
Mexico .....Half sea, half land.
Shide .....Mostly sea, polar archipelago, Greenland?
San Fernando .....Half sea and land, largely polar.
Bombay .....Mostly land—Siberia, Tibet.
Batavia .....Deep sea, east of Asia.
Mauritius .....Siberia, India, Indian Ocean.
Cape of Good Hope.....Polar sea, Europe, Africa.

Still assuming what we know now to be a slightly erroneous origin and assuming constant speed for small distances and with nine minutes as the time from the origin to Victoria, he made the following table:

Arc.	Chord.	Time of passage in minutes.	Speed.		
			Arc degrees. Min.	Chord. Min.	Arc radians. Min.
Victoria..... 16°	.28	9 00 00	1.8	.031	.031
Toronto..... 40°	.68	22 22 22	1.8	.31	.31
Mexico..... 49°	.83	00 29 28	1.7	.29	.30
Shide..... 70°	1.15	39 42 41	1.8	.29	.31
San Fernando. 77°	1.25	44 44 44	1.75	.28	.305
Bombay.. ...105°	1.59	55 55 57	1.9	.28	.33
Batavia .....108°	1.62	00 65 75	{ 1.66 / 1.44 }	.23	....
Mauritius ....145°	1.91	90 00 88	1.63	.215	.284
Cape of Good Hope.....165°	1.98	88 89 83	1.9	.226	.33

In the above table $\frac{\text{chord}}{\text{min.}}$ and $\frac{\text{arc radians}}{\text{min.}}$ may be reduced to $\frac{\text{kilom.}}{\text{sec.}}$ by multiplying by 1.06; $\frac{\text{arc degrees}}{\text{min.}}$ may be reduced to $\frac{\text{kilom.}}{\text{sec.}}$ by multiplying by 1 84.

[104] Fifth Report of Committee on Seismological Investigations of the British Association for the Advancement of Science, 1900, p. 69.

[105] Publications of Earthquake Investigation Committee in foreign languages, no. 13, 1903, pp. 121-124.

[106] Fifth Report of Committee on Seismological Investigations of the British Association for the Advancemeent of Science, 1900, p. 77.

Computing these velocities by the above formula, the speed of transmission of surface waves is seen to vary between 3.1 and 3.3 kilometers per second, or nearly two (1.95) statute miles per second, a rate agreeing substantially with those reached independently from the several computations cited above.

DISTURBANCE OF EARTH'S SURFACE

The seismic disturbances traversed the rocks of the earth's crust to all parts of the world from the origin in Yakutat Bay, where Prof. John Milne has estimated that during the faulting one or two cubic miles of rocky material[107] were disturbed and molar disturbances took place.[108] No seismograph known to have been in operation in September, 1899, failed to record these shocks if that type of instrument was capable of registering them.

The disturbances may be divided into two classes: (*a*) those that seismologists infer to have gone directly through the earth, and (*b*) those that follow the earth's outer crust. These are indistinguishable at distances of less than 650 miles. Beyond that distance—for example, at Victoria—the seismograph records show slight disturbances arriving very soon (preliminary tremors) and great motion after a longer time (principal portion or large waves). The preliminary tremors come directly through the earth, along chords. They are generally thought to be longitudinal, compressional vibrations. They have a shorter distance to go and also move at a faster rate than the large surface waves. On September 3, 1899, these direct waves traversed the chord from Yakutat to Victoria in 3½ to 4½ minutes, the large waves, moving presumably along the arc, taking 13 minutes and 29 seconds to reach Victoria through the earth's outer crust.

These large waves of the principal portion vibrate transversely to the line of propagation. They were formerly thought to make the earth's crust actually rise in long, undulating earth-waves. For example, it was estimated[109] that the large waves of the Yakutat Bay earthquake of September 3 passed through Shide, England, as earth-waves about 28 miles in length and 11 2/5 inches high (45 kilometers by 29 centimeters) The earth-waves of the great shock on September 10 at Shide were computed as 74 miles long and 15 2/5 inches high (120 kilometers by 39

[107] Nature, vol. 75, 1907, p. 224.

[108] Seventh Report of Committee on Seismological Investigations of the British Association for the Advancement of Science, 1902, p. 62; Nature, vol. lxvii, 1902-1903, p. 69.

[109] J. Milne: Fifth Report on Seismological Investigations of the British Association for the Advancement of Science, 1900, p. 83.

centimeters), and the waves that followed as about 28 miles long and 17 inches high (45 kilometers by 43 centimeters).

AREA DISTURBED BY 1899 EARTHQUAKES

DISCUSSION OF MAPS

Figures 3 and 4 show the minimum area within which the earthquake of September 3 and the great earthquake of September 10 are known to have been felt. The locations of observers are shown by the symbol (*). The outer boundaries are indicated by solid lines only where evidence shows that beyond that line the shocks were insensible. Dotted lines are used as boundaries where information is lacking. If much of this area had not been a nearly empty wilderness in 1899 and if the investigation could have begun at once instead of after seven or eight years, many more of the men who were inside or just outside the shaken area might have been found. Their evidence would surely increase rather than decrease the areas of sensible disturbances for the several earthquake shocks.

Nothing on the maps depends on hearsay evidence. Each symbol represents a reliable observer who has been directly interviewed, or corresponded with, or who has replied to an earthquake circular or published an earthquake record in some report.

It is only on the southeast, near Sitka and Sumdum (figure 4); on the north, near Dawson, Circle, and Rampart, and on the west, between Seldovia and Kodiak, that even partial outer boundaries could be drawn. In other directions the shocks were probably sensible even farther than shown, for they were felt everywhere along a chance line of points of observation like the Klondike trail, to the east of which there were probably no human beings in 1899.

One reason for incompleteness of data is that at distances of over 250 miles these shocks were often so weak as to be imperceptible to persons engaged in one occupation, while to others they were sensible. At Sitka, for example, the great earthquake of September 10 was felt by Bishop Rowe, who was lying down, but not by Doctor Georgeson, who was walking out of doors. Two hundred and fifty miles northwest of Yakutat Messrs. Brooks and Peters, of the U. S. Geological Survey, did not feel the September 3d earthquake, though they heard the boom of avalanches caused by it and at exactly the proper time. These men, though trained scientific observers, did not feel the great earthquake of September 10, probably because they were on the march. These shocks were felt, how-

ever, 60 miles farther from Yakutat, along the same line, jarring apparatus and causing lamps to swing in the U. S. Weather Bureau office at Eagle and being observed by prospectors panning gold in the Forty-Mile district.

Local topographic or geological conditions also explain observation or failure at great distances. In the Koyukuk and lower Yukon observations (shown on figure 3 as detached areas) weak tremors seem to have been naturally amplified in the unconsolidated Pleistocene silts.

SQUARE MILES SHAKEN

The shocks of the great earthquake on September 10 (figure 4) were felt at all places within 250 miles of Yakutat and at other points up to 480 miles from the origin. This minimum area of sensible shocks includes 216,300 square miles on the land alone, and if an equal area in the Pacific Ocean was disturbed (figure 1) the minimum area includes 432,500 square miles. This takes no account of the detached observation on Lake Chelan, Washington.

The observations by Mr. Schrader on the Koyukuk and by Father Amcan on the lower Yukon are detached areas beyond the compact minimum area of the shock of September 3 (figure 3). If these points, 670 and 730 miles respectively from Yakutat, were included, together with other points equally distant, a circular area with a radius of 700 miles was shaken, and this area included about 1,539,000 square miles. This is considered quite probable, first, because this part of Alaska was, in 1899, an almost vacant wilderness, and, secondly, because people in Alaska become so accustomed to earthquakes that they do not notice or record weak tremors at great distances like these. In Alaska, too, there were no high buildings to naturally amplify weak tremors not sensible to persons on the ground, as was the case in La Crosse, Wisconsin; Boston, Massachusetts, and New York City[110] during the Charleston earthquake of 1886.

The inclusion of the disturbed areas within circles follows the assumption that Yakutat Bay was the center of disturbances, outside of which there was little or no movement. This hypothesis seems warranted, in the absence of other evidence, and the plotting of the minimum areas (figures 3 and 4) bears this out somewhat. An alternate hypothesis would consider the tectonic disturbances to extend in the direction of the axis of the Saint Elias-Chugach range. Facts are not available for settling absolutely between these hypotheses.

[110] C. E. Dutton: Ninth Annual Report of the U. S. Geological Survey, 1889.

Relation to other Alaskan Earthquakes

Alaska has been classified as only peneseismic by Comte F. de Montessus de Ballore,[111] who says that "the only important earthquake known is that of September, 1899, at Yakutat Bay." There are other severe earthquakes, however, and the same seismologist, after cataloguing 131,292 earthquakes and 10,499 epicenters up to the end of 1897, assigns 12 earthquakes to 7 epicenters in Alaska and 86 earthquakes to 15 epicenters or localities so considered in the Aleutian Islands[112] (figure 9).

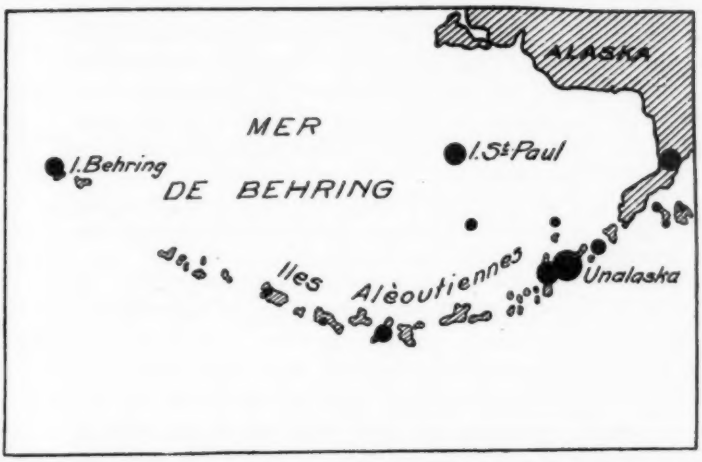


FIGURE 9.—*Habitual Epicenters in Aleutian Islands and Bering Sea* (after de Montessus de Ballore)

These shocks are presumably chiefly volcanic rather than tectonic

Dr. G. K. Gilbert credits Alaska with nine shocks of destructive rank[113] since the beginning of the last century, stating that the record is fragmentary and may omit more than it includes.

The first recorded earthquake in Alaska is that stated by Grewingk[114] to have occurred in the Sannak and Shumagin islands, south of the

[111] Les Tremblements de Terre, Paris, 1906, p. 414.

[112] Introduction à un essai de description sismique du globe et mesure de la sismicité. Beiträge zur Geophysik, band iv, p. 363.

[113] Earthquake forecasts, Science, N. S., vol. xxix, 1909, pp. 125-126.

[114] C. Grewingk: Treatise on the volcanic character of certain regions of the Russian possessions. Proceedings of the Mineralogical Society of Saint Petersburg, 1850; translated by Ivan Petroff in Report on seal and salmon fisheries and general resources of Alaska, Senate Document 59, 45th Congress, 1st session, p. 313; House Document 92, 55th Congress, 1st session, part iv, p. 313; Tenth Census, 1880, vol. 8, pp. 95-96.

Alaska Peninsula, in 1788, when "there were no volcanic phenomena reported, but on the 27th of July a flood submerged the islands of Sannak and Ounga and a portion of the peninsula (evidently a tidal wave, owing to earthquake)." Dall[115] states that during this inundation many natives lost their lives and that hogs on Sannak Island were drowned.

Grewingk,[116] Perret,[117] and Dall[118] have listed earthquakes, mostly in connection with volcanic eruptions, in 1790, 1792, 1796, 1802, 1812, 1817, 1818, 1820, and 1826. In 1827 there was an earthquake on Copper Island in June, but it is not stated whether in association with a volcanic eruption or not. On April 2, 1836, and in August of the same year earthquakes were felt on the islands of Saint Paul and Saint George, in the Pribilof group, during which it was impossible to stand erect.

In 1843 occurs the first precise scientific observation of a tectonic earthquake in Alaska instrumentally recorded that has come to the writer's attention. This is quoted by Perret, from whose account[119] the following is translated:

> "On the 15th of December, at 1.20 a. m., there were two light shocks on Sitka Island, during which the unifilar and bifilar magnetometers oscillated in a vertical plane.
>
> "There was a second shock an hour and twenty-five minutes later. The position of the vertical-force needle changed 55 parts during the first two shocks."[120]

On December 16, 1843, at 1.30 p. m., there was a feeble earthquake at New Archangel (Sitka). At 4 p. m. there was a stronger shock, lasting three seconds; the houses were rent; the workman saw the trees apparently move back and forth during a calm. At the warm springs, 28 versts from the town, other persons observed these shocks, but 35 minutes earlier.[121]

In 1847 a general earthquake was felt on the Alaskan coast, being very severe at Sitka.[122] This is doubtless one of the shocks referred to by the newspapers of 1899, which allude to the Yakutat Bay earthquakes as "the most severe since the time of the Russians."

On October 22, 1849, there was a violent earthquake, lasting all night,

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[115] W. H. Dall: Alaska and its resources. Boston, 1870, pp. 310, 467.

[116] Op. cit., pp. 311-315.

[117] Alexis Perret: Documents sur Les Tremblements de Terre et Les Phenomenes Volcaniques des Iles Aleutiennes, de la peninsule d'Alijaska et de la cote No. d'Amerique. Acad. Imp. de Dijon, deuxieme serie, tome xiii, 1865, pp. 158, 216-237.

[118] Op. cit., pp. 466-470.

[119] Alexis Perret, Mem. Acad. Imp. de Dijon, 2me. ser., tome xiii, 1865, p. 238.

[120] Annuaire magnétique et météorologique du corps des ingénieurs des mines de Russie, année 1843, p. 553.

[121] Comm. de M. Osten-Sacken.

[122] W. H. Dall: Op. cit., p. 342.

in the Commander Islands. This is listed by Alexis Perret,[123] as are the succeeding earthquakes of 1853, 1857, 1859, 1861, and 1866.

On November 13, 1853, about 100 kilometers[124] east of Ikogmute, on the lower Yukon, there was a shock at the village of Paimüt, moving from south to north. Earthquakes there are infrequent, the last having been felt sixty years before. The above note is from a meteorological register then kept at Ikogmute by P. Netzvetor.[125]

On September 8, 1857, at 11 a. m., two earthquakes were felt at Saint Paul (now called Kodiak), on Kodiak Island. They were several seconds apart, the second being rather severe, though no damage was done.

On August 8, 1859, there was a light shock, lasting several seconds, on Bering Island.

Sitka was again shaken by an earthquake on April 21, 1861, at 9.36 a. m.[126]

On May 3, 1861, there was a light shock on Saint George, Pribilof Islands, with a subterranean noise. There was a light shock on Atka Island at 8.30 a. m., on May 10, 1861, followed by another on August 21, this last with a subterranean noise.[127]

In 1866, and before October 22 of that year, there was an earthquake near Kodiak. Further details are lacking.

In 1867 an earthquake was felt at Russian Mission (Ikogmute), on the lower Yukon, where the shock of September 3, 1899, was also felt, and near which was recorded the shock of 1853 and another sixty years before. W. H. Dall[128] was on the Yukon River at about 11 o'clock on the night of July 19, and reports that it felt as if the boat had struck a snag. This has also been reported by Frederick Whymper.[129] The shock was severe enough at the mission to throw books and other articles from the shelves.

In 1868 Becker[130] states that "during a slight earthquake the elevation is said to have amounted locally at Unga to over 20 feet."

Petroff[131] mentions a violent earthquake at Sitka in the autumn of 1880.

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[123] A. Perret: Op. cit., pp. 239, 243, 244, 246, 247, 251.

[124] Really only 38 miles.

[125] M. Vesselofski, Permanent Secretary of Academy of Sciences, Saint Petersburg.

[126] Ann. meteor. et magn. de Russie, 1861, p. 455.

[127] Notes extraites du comte-rendu de la Compagnie russe-américaine pour 1861, par M. le baron Osten-Sacken.

[128] Alaska and its resources, Boston, 1870, pp. 118, 470; The Yukon Territory, London, 1898, p. 118.

[129] Journal of the Royal Geographical Society, London, vol. xxxviii, 1868, p. 234. Travel and adventure in the Territory of Alaska, New York, 1869, p. 266.

[130] G. F. Becker: Reconnaissance of the gold fields of southern Alaska. Eighteenth Annual Report, U. S. Geological Survey, part iii, 1896-1897, p. 19.

[131] Ivan Petroff: Alaska, its population, industries, and resources. Tenth Census of the United States, 1880, vol. viii, p. 91.

In 1883 there are said[132] to have been earth tremors and a 30-foot water wave in Cook Inlet in connection with an eruption of the Saint Augustine volcano there. This was on October 6, 1883.

Deckert shows many of the earthquakes referred to above on his map of earthquakes in North America,[133] and in addition lists three earthquakes in the Aleutian Islands in 1877, 1878, and 1879, all presumably volcanic shocks. A fourth was felt at Kodiak in 1889.

F. G. Plummer's list of earthquakes on the Pacific coast,[134] as reprinted by E. S. Holden,[135] contains nearly all of the earthquakes thus far cited and a few others, most of them in connection with volcanic outbursts, as during the eruption of Pauloff in 1786; at Kaviak in 1854; at Black Peak, near Chignik, on August 28, 1892; at Unalaska, September 23, 1892, and on Saint Augustine volcano in the summer of 1893.

Several of the Alaskan shocks referred to above are also recorded in the yearly lists of Pacific Coast earthquakes from 1888 to 1898 by E. C. Holden,[136] T. F. Keeler,[137] and C. D. Perrine.[138]

There have doubtless been many other earthquakes in Alaska, but no list or description of them is available. The Russian records of various sorts are a great unused storehouse of information of this kind. The records of the voluntary Weather Bureau observers of the U. S. Department of Agriculture doubtless also contain much information concerning other earthquake shocks in Alaska at various places and times between the time of the American purchase of Alaska and the end of the century.

In connection with the gathering of information concerning the seismic disturbances of 1899 at Yakutat, which are the subject of this paper, a considerable amount of unpublished data has come into my hands concerning other earthquakes in Alaska. I have thought it best briefly to summarize this, both because it enables me to place the Yakutat Bay shocks of 1899 in their proper setting as a series of especially severe tectonic shocks in an earthquake-shaken region, where there are both tectonic and volcanic earthquakes, and because I feel that this information, fragmentary and incomplete as it is, should be placed on record for the use of those interested in seismology. In 1901 a magnetograph was

[132] George Davidson: Science, vol. iii, 1884, pp. 186-189.

[133] E. Deckert: Zeitschrift der Gesellschaft für Erdkunde zu Berlin, 1902, Tafel 5 and pp. 367-389.

[134] Reported earthquakes on the Pacific coast. Publications, Astronomical Society of the Pacific, vol. viii, 1896, p. 78.

[135] A catalogue of earthquakes on the Pacific coast, 1769 to 1897. Smithsonian Miscellaneous Collections, 1087, vol. xxxvii, 1898, pp. 1-253.

[136] American Journal of Science (series 3), vol. 37, 1889, pp. 392-402. Bulletin no. 95, U. S. Geological Survey, 1892.

[137] Bulletin no. 68, U. S. Geological Survey, 1890.

[138] Bulletins nos. 112, 114, 129, 147, 155, 161, U. S. Geological Survey, 1893 to 1899.

installed by the U. S. Coast and Geodetic Survey at Sitka, and on April 29, 1904, a Bosch-Omori seismograph, so that in the future the earthquake records from Alaska will be fairly complete.

In the preceding list the earthquakes reported by Grewingk, Perret, Dall, Petroff, and Becker in 1788, 1843, 1847, 1853, 1857, 1861, 1866, 1867, 1868, and 1880 are doubtless tectonic. Some may have been world-shaking. The others are doubtless largely volcanic and merely local.

Other tectonic shocks in Alaska which were probably world-shaking, like these in Yakutat Bay in 1899, and which have not previously been described, are mentioned below. There were no volcanic phenomena of Mount Wrangell or the Aleutian volcanoes at these times.

The Chugach earthquake of October 9, 1900, was felt between 2 and 3 a. m. in the Chugach Mountains and all about the Gulf of Alaska from Yakutat Bay to Kodiak Island. The minimum area disturbed was about 121,000 square miles on the land. The seismograph stations at Victoria and Toronto recognized its Alaskan origin, and instruments throughout the world recorded it.[139] The seismograph record was referred to by Prof. John Milne,[140] and seismograms at Laibach, Austria,[141] and Tokio, Japan,[142] have been published. The latter is reproduced in this article as the upper seismogram in plate 30.

The Lynn Canal earthquake of September 24, 1907, was felt at Skagway at 4.02 a. m., and at Sitka at 3.59½, where the U. S. Coast and Geodetic Survey seismograph recorded it.

The Prince William Sound earthquake of February 14, 1908, was felt at Valdez about 1.25 a. m.; also throughout Prince William Sound and eastward to Controller Bay. Two submarine cables in Valdez fiord were broken by faulting in 600 to 700 feet of water. Seismographs recorded this shock at Sitka, Victoria, Toronto, Baltimore, etcetera.

The Controller Bay earthquake of May 14, 1908, occurred at 11 p. m., and was sensible along the Alaskan coast from Seward to Sitka. Seismographs recorded it at Sitka, Victoria, Toronto, Baltimore, Cheltenham, Washington, Porto Rico, the Hawaiian Islands, and doubtless elsewhere. Other Alaskan earthquakes are mentioned in the following list.

The place of observation was not usually, of course, the origin of the earthquake, and it is not known how many of these shocks are volcanic and how many tectonic. Many of the places referred to here are shown on figure 8.

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[139] Seismological Committee of the British Association for the Advancement of Science, circular 3, 1901, pp. 63, 65, 69, 73, 74, 77, 85, 87, 89.

[140] Nature, vol. lxv, 1902, p. 203.

[141] Beiträgen zur Geophysik, Ergänzungsband I, 1902, tafel v, fig. 13.

[142] Publications of Earthquake Investigation Committee in foreign languages, no. 21, 1905, fig. 51.

Observers.	Places.	Years.	Dates.	Remarks.
T. G. White	Yakutat	1893.	March	
R. W. Beasley	Yakutat	1894.	November 3.	Three light shocks.
John Shepard	Orca	1896.	May	Very severe; earthwaves.
R. W. Beasley	Yakutat	1897.	January 11	Severe, shaking the house.
C. P. Coe	Wood Island		Winter	7 p. m.
H. H. Pitts	Selkirk		May 6	Buildings vibrated and gravel slid in river banks.
Prospector	Tyonek	1898.	About Aug. 15	Slight.
Rev. F. R. Falconer	Susitna Station		August	Trees swayed violently on calm, windless day.
Charles Brown	Valdez		August 24	Heavy earthquake at 10 p. m.
J. E. Spurr	Katmai		October 15	Near Hot Springs.
Oscar Rohn	Katmai		October	
F. E. Fuller	Skagway		Oct'r-Nov'r.	7.30 a. m., slight.
S. S. Sharick	Juneau			Northeast, 15 seconds; 15 minutes later, 8 to 10 seconds.
H. S. Tibbey	Unga	1899.	March 18	Four seconds, motion west to east.
H. S. Tibbey	Unga		April 1	4.45 p. m., east to west. Threw light articles off shelves.
H. S. Tibbey	Unga		June 8	10 a. m., north to south, light.
H. S. Tibbey	Unga		July 14	2.55 a. m. Two shocks north to south, 6 seconds, rumbling noise preceding.
Prospector	Tyonek		July 11	Severe.
W. A. Sawtelle	Unalaska		July 14	2.15 a. m.
H. S. Tibbey	Unga		Sept'r 22	9.30 p. m., severe, north to south.
Capt. J. S. Herron	Alaska Range		Oct'r 21-22	Shocks, with low, rumbling noises.
C. K. Corbusier	Tanana			Bottles rattled on shelf, same at Fort Gibbon.
Capt. R. McCoy	Fort Gibbon		November 1.	11.05 p. m.
L. S. Camicia	Valdez	1900.	July 30	1 p. m.
R. W. Beasley	Yakutat		August 7	4.15 p. m., light.
R. W. Beasley	Yakutat		August 8	5.25 p. m., light.
R. W. Beasley	Yakutat		August 9	7.40 p. m., light.
R. W. Beasley	Yakutat		August 9	11 p. m., light.
August Groot	Cross Sound, 80 miles west of Juneau.		August	Light shocks.
Prospector	Tyonek		October 7	Severe shock.
T. G. White	Katalla		October	
L. L. Bowers	Kodiak		October 11	
L. L. Bowers	Kodiak		October 12	5.15 a. m.
H. P. Cope	Kodiak		October 13-14	
C. P. Coe	Wood Island		October 14	
L. L. Bowers	Kodiak		October 14	2.30 and 5.15 a. m.
L. L. Bowers	Kodiak		October 15	8 and 8.15 a. m.
L. L. Bowers	Kodiak		October 22	During evening.
L. L. Bowers	Kodiak		October 23	3 a. m.
L. L. Bowers	Kodiak		October 24	Slight shocks during day.
L. L. Bowers	Kodiak		October 26	Slight during day and night.
R. W. Beasley	Yakutat		December 17	5 a. m.
L. L. Bowers	Kodiak		December 27	12.05 a. m., short and heavy.
R. W. Beasley	Yakutat		December 31	1.40 a. m.
H. W. Mellen	Prince of Wales Island.		Fall 1900, spring 1901.	Frequent rumbling noises and light tremblings.
L. L. Bowers	Kodiak	1901.	January 17	8.30 a. m.
R. W. Beasley	Yakutat		January 19	7 a. m.
R. W. Beasley	Yakutat		January 24	5 a. m.
Capt. R. McCoy	Fort Gibbon		March (?)	Hard earthquake.
L. L. Bowers	Kodiak		April 4	6.30 a. m.
L. L. Bowers	Kodiak		May 30	7.15 p. m., light.
G. F. Baker	Fairbanks		July 12	8.30 a. m.
L. L. Bowers	Kodiak		July 23	4.25 p. m.
Simeon Post	Valdez		September	
L. S. Camicia	Valdez		September	2.50 p. m.
R. W. Beasley	Yakutat		Sept'r 28	12.30 p. m.
Adolph Stecker	Bethel	1902.	February	
Prospector	Tyonek		April 18 or 19	Slight.
Brother Constantine	Koserefsky		December 6	Thought building would be crushed.

Observers.	Places.	Years.	Dates.	Remarks.
Rev. A. R. Hoare	Tanana		Winter 1902–1903.	
R. W. Beasley	Yakutat	1903.	March 10	6. a. m.
J. H. Robinson	Eagle		Spring	
Chas. Suironstad	Valdez		March	Drove people into streets.
W. A. Dickey	Landlock		May	
L. S. Camicia	Valdez		June 2	3.45 p. m., strong shock; direction, northeast to southwest.
L. S. Camicia	Valdez		July 13	11.40 a. m.
G. C. Martin	Dry Bay		July	Cliffs fell.
G. C. Martin	Enochkin Bay		August	Waves on still water of bay.
L. N. Gordon	Seward		1903	Very severe.
R. W. Beasley	Yakutat		Sept'r 10	5 a. m.
Brother Constantine	Koserefsky	1904.	December 8	Violent shaking of log church.
Dr. J. H. Romig	Nushagak		1904–1905	
L. S. Camicia	Valdez	1905.	February 6	7.20 a. m.
E. E. Ritchee	Seward		August	20 to 30 seconds.
L. S. Camicia	Valdez		November 22	At midnight.
Rev. N. N Amcan	Onhagmute		December 8	
Adolph Stecker	Bethel		December 9	
Rev. John Hinz	Ogavik, Kuskokwim.		December 8	House rocked; also felt 80 miles away at Bethel.
L. S. Camicia	Valdez	1906.	May 2	5 a. m.
Mrs. J. R. Heckman	Loring		August 6–7	10 p. m. and 3 a. m.
R. S. Tarr	Yakutat Bay		Summer	Slight tremors.
J. R. Hayden	Fairmont Island		Sept'r 19	2 p. m.
L. S. Camicia	Valdez		October 25	2 10 a. m.
J. J. Tolbert	Dutch Harbor		November 2	Slight, 12.30 a. m.
J. J. Tolbert	Dutch Harbor		December 20	Slight, during day.
C. L. Boudry	Cold Bay		December 25	7 a. m.
J. J. Tolbert	Dutch Harbor		December 22	7 a. m. and 7.55 p. m.
C. L. Boudry	Cold Bay		December 28	10 p. m.
Judge Lars Gunderson	Mary's Igloo, Hot Springs, and Shelton.		March	
J. J. Tolbert	Dutch Harbor	1907.	August 22	11.25 a. m.
Dr. J. H. Romig	Nushagak		1906–1907	
Dr. J. H Romig	Nushagak		September 6.	
S. Kilborn	Killisnoo		October 5	Light shocks.
J. R. Hayden	Prince William Sound.		Fall	
J. D. Jefferson	Valdez		December 10	
Lieut. L. H. Hansen	Fort Liscum	1908.	May 3	7 p. m., 10 seconds.
Lieut. L. H. Hansen	Fort Liscum		May 4	7.35 a. m., 15 seconds, slight shock, with rumbling sounds.
L. S. Camicia	Valdez		May 4	7 a. m.
Rev. N N. Amcan	Kuskokwim River		June 8	
J. J. Tolbert	Dutch Harbor		March 15	Three shocks, one at 3 o'clock and two about 7.
B. F. Baker	Hot Springs		December 20	6 a. m., sharp shock.
E. A. Rasmussen	Yakutat	1909.	February 16.	Stopped clocks.
E. A. Rasmussen	Yakutat		May 6 (?)	Spilled water out of reservoir on stove and from barrels outdoors.
Lawrence Martin	Russell Fiord, Yakutat Bay.		July 16	Slight, with booming noise, as of avalanche.

Comparison with other Great Earthquakes

The Yakutat Bay earthquakes of September, 1899, are in some respects like and in some respects different from other great seismic disturbances. They rank among the greatest North American earthquakes (figure 1) and stand high among the world's seismic disturbances in intensity and

area affected. The following is a list of the areas affected by some of the larger tectonic earthquakes of historic times:

Charleston, 1886, about 2,800,000 square miles:
Felt at La Crosse, Wisconsin, Boston, Massachusetts, Cuba, and Bermuda. Maximum radius of propagation, 700 to 950 miles.

Lisbon, 1755, about 2,240,000 square miles:[148]
Felt in Great Britain, throughout western Europe, and in northern Africa. Maximum radius of propagation, 700 to 1,200 miles.

India, 1897 (Assam), about 1,750,000 square miles:
900-mile radius of propagation.

Alaska, 1899, about 1,539,000 square miles:
700 (670 to 730) mile radius of propagation. (Minimum land area, 216,300 square miles; land and sea area, about 432,500 square miles.)

India, 1905 (Kangra), about 1,500,000 square miles.

New Madrid, 1811-1812, about 1,250,000 square miles:
Felt at Charleston, South Carolina, Richmond, Virginia, Washington, District of Columbia, Louisville, Kentucky, Fort Duquesne (Pittsburg), Detroit, Fort Dearborn (Chicago), etcetera.

Sonora, Mexico, 1887, about 500,000 square miles:
Felt at Durango, Mexico, Fort Davis, Texas, Las Vegas and Santa Fe, New Mexico, Prescott and Yuma, Arizona, and generally within about 400 miles.

California, 1906, about 372,700 square miles:
Felt in Coos Bay, Oregon, Los Angeles, California, and Winnemucca, Nevada. Radius of propagation, 350 to 400 miles.

Japan, 1891, about 330,000 square miles:
Radius of propagation, 323 miles.

Riviera, 1887, about 219,000 square miles:
Radius of propagation, 264 miles.

In connection with the Yakutat Bay, Alaska, earthquakes of September, 1899, there were physical changes, including submergence, as in the Indian earthquake of 1819 and the Jamaica earthquakes of 1692 and 1907. There was elevation, proved by uplifted beaches, cliffs, sea caves, and marine animals attached to the rocks, as in Darwin's South American earthquakes of 1822, 1835, and 1839. No other historic earthquake beside that of Alaska reveals an uplift of as much as 47½ feet at one time. There were new reefs, as in the New Zealand earthquake of 1855. There was surface faulting, as in the Calabrian earthquake of 1783, the New Madrid earthquakes of 1811-1812, the Owens Valley earthquake of 1872, the Mexican earthquake of 1887, the Japanese earthquake of 1891, the earthquake of 1896 in Iceland, the Indian earthquakes of 1897 and 1905, and the San Francisco earthquake of 1906. There was disturbance of surface and underground drainage, with formation of sand vents and craterlets, as in the Charleston earthquake of 1886, as well as several listed above. There were destructive water waves, or tsunami, as in the Lisbon earthquake of 1755, the Japanese earthquake of 1896, and others.

[148] Perhaps 500,000 square miles less; Oldham (Memoirs, Geol. Survey of India, xxix, 1899, p. 376) says perhaps only 1,000,000 square miles.

The glacial oscillations which have resulted from these Yakutat Bay earthquakes, including the initiation of the eight-mile retreat of Muir Glacier and other ice-tongues of Glacier Bay, and the great spasmodic advances of part of the Malaspina and at least six other glaciers in Yakutat Bay, find no known parallel among the world's historical earthquakes. These advances, however, explained by abnormal accession to the glacier reservoirs through earthquake avalanches, must surely find a parallel in other regions of lofty, snow-capped mountains which are still so young as to be frequently faulted and shaken by earthquakes. Future studies of earthquakes in Alaska, the Alps, the Caucasus, the Himalayas, etcetera, will probably reveal such glacial oscillations.

Relation of Yakutat Bay Earthquakes to Life

In contrast with practically all the great earthquakes of historic times, the Yakutat Bay shocks of September, 1899, stand conspicuous for the absence of loss of life and destruction of property which accompanies most seismic disturbances. This was because they took place in an area largely wilderness at that time and because the frontier inhabitants lived in tents, in log cabins, or in low frame buildings. The minimum land area shaken by the great earthquake of September 10 (216,300 square miles, figure 4) contained a population of 20,000 persons or less.[144]

In 1891, during the earthquake in Japan, 7,279 people were killed and 17,393 injured, 197,000 buildings were destroyed and 84,000 damaged. Twenty-seven persons lost their lives in the Charleston earthquake of 1886, 56 others perishing by cold, exposure, etcetera, out of a city of 50,000 to 55,000. Many houses were destroyed, many more damaged, and 13,000 chimneys thrown down. In the first (Assam, 1897) Indian earthquake practically all the buildings in 145,000 square miles were laid in ruins. In the second (Kangra, 1905) Indian earthquake 18,815 lives were lost, and the destruction of property was enormous, the number of buildings destroyed being 112,477. In California,[145] in 1906, between one and two hundred thousand people were made homeless, but only 709 lives were lost directly because of the earthquake. There was tremen-

[144] Twelfth Census of the United States, vol. I, p. 426, shows 11,668 in the disturbed area in Alaska out of 63,592, the total population of Alaska in 1900. The Atlas of Canada, pp. 4 and 13, shows 8,935 persons in the shaken part of Yukon Territory in 1901, the number in the shaken part of British Columbia not being given. Presumably the population was nearly as great in the two previous years, although there may not have been the same number of gold-seeking prospectors in 1899 as in 1900 or 1901.

[145] G. K. Gilbert: Science, N. S., xxix, 1909, p. 137.

R. L. Humphrey and Frank Soulé: The San Francisco earthquake and fire, Bulletin 324, U. S. Geological Survey, 1907, pp. 61 and 138.

A. G. McAdie: Catalogue of earthquakes on the Pacific coast, 1897 to 1906, Smithsonian Miscellaneous Collections, vol. xlix, 1907, p. 47.

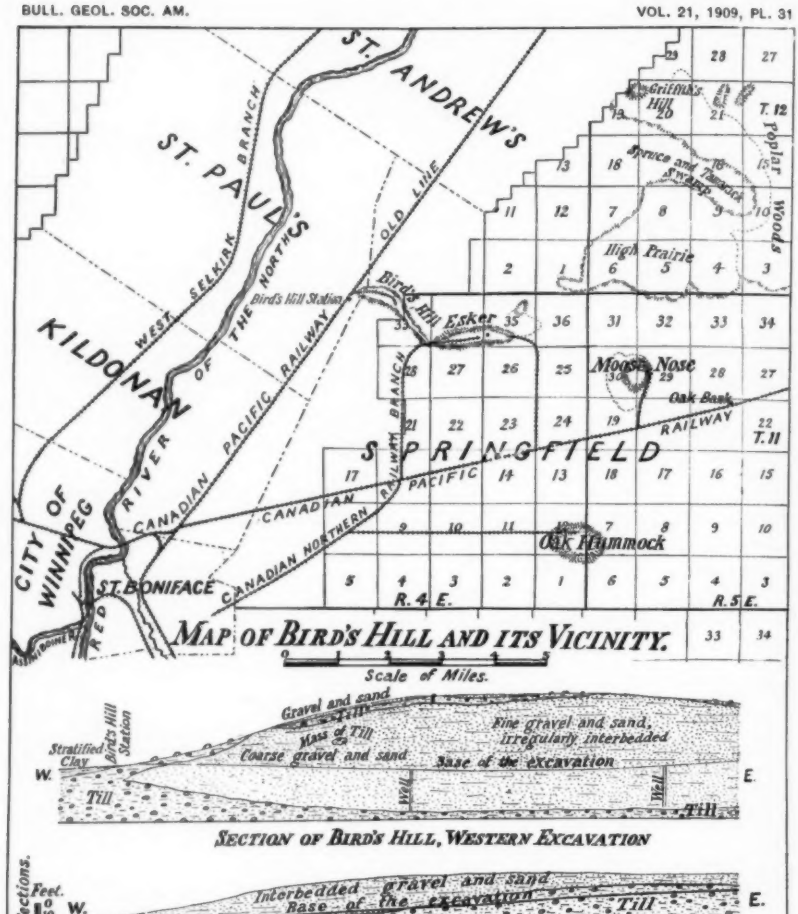
dous destruction of structures, 25,000 buildings being destroyed in the earthquake and fire, with an estimated value of between 139 million and 500 million dollars. In the Riviera earthquake, in 1887, 640 people were killed and over 570 injured, 155 houses were rendered uninhabitable in Mentone, 61 in Nice, and many others elsewhere, so that the property loss was over $5,000,000. Lyell states 60,000 people were killed in six minutes in the Lisbon earthquake of 1755, practically the whole city being thrown down. About 20,000 lives were lost in the Calabrian earthquake of 1688, about 43,000 in 1693, between 32,000 and 60,000 in 1783, 800 in 1905, while the loss of life in 1908 was stated as 100,000.

In contrast with all this, there was no recorded loss of life as a result of the Yakutat Bay earthquakes, and the most serious property damage known, aside from the loss of a rowboat, some tents, provisions, and clothing by the eight prospectors in Disenchantment Bay, was the shifting of the roof of an uninhabited log cabin in outer Yakutat Bay and the cracking of a few chimneys and slight damage to a wharf in Skagway. The great earthquakes of New Madrid, Sonora, South America, and New Zealand, likewise in rather thinly populated districts, would doubtless be more like the Alaskan case in slight damage to the human race.

In Yakutat Bay lower forms of life, particularly marine animals and plants, were destroyed by millions. Many fish were killed by the shocks or washed up by the water waves. Annual land plants and forest trees were killed by the water waves or by submergence of the coast. Human life, however, was almost unaffected, excepted through nervous strain.

The Yakutat Bay earthquakes of September, 1899, do not contribute to the problems of warning and safety for the human race during the seismic disturbances accompanying earth movements. They are in the unfortunately small class of world-shaking disturbances of which one may read without turning with a shudder at the loss of human life.

Evidences of older faulting, older uplifts, older submergences, and older earthquakes in Yakutat Bay lead to the expectation of future earthquakes there from future earth movements in this growing mountain range. The region has few inhabitants, nor is it likely to be much visited except as its wonderful glaciers (figure 5) attract tourists, especially now that the well known Muir glacier has lost much of its scenic interest. Future earthquakes, therefore, are not likely profoundly to influence life, as would be the case if Yakutat Bay and other parts of Alaska were thickly populated as are such earthquake regions as Japan, India, the East Indies, Asia Minor, the Balkan Peninsula, Italy, Spain, the West Indies, western South America, Mexico, and California.



MAP AND SECTIONS OF BIRDS HILL, MOOSE NOSE, AND OAK HUMMOCK, NEAR WINNIPEG, MANITOBA

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BIRDS HILL, AN ESKER NEAR WINNIPEG, MANITOBA[1]

BY WARREN UPHAM

(Presented by title before the Society December 29, 1909)

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INTRODUCTION AND TOPOGRAPHIC DESCRIPTION

Last August, during the meeting in Winnipeg of the British Association for the Advancement of Science, an excursion by 16 of the geologists in attendance was taken for examination of the esker named Birds Hill, adjoining the station and little village of Birds Hill, 8 miles northeast of Winnipeg, on the old and original main line of the Canadian Pacific Railway. This esker, a ridge of sand and gravel, extensively excavated for building and street uses, has a length of about 4 miles to the southeast and east from that station. Both the old line of the Canadian Pacific Railway and its newer line on the south have spur tracks or short branch lines for bringing the sand and gravel from the many and long excavations by which much of this esker at each end and along the greater part of its course is being removed for economic purposes.

The height of the esker is mostly 40 to 50 feet above the level of the very flat Red River Valley plain. Its width, including the generally

[1] Manuscript received by the Secretary of the Society December 30, 1909.

smoothly rounded top and the moderately steep or mostly very gentle slopes on each side, ranges from 500 to 1,500 feet, being mainly about 1,000 feet. Thus it differs from a majority of eskers in being broader and lower and in having less steep sides than the average type of its class of drift formations.

Because Birds Hill is the nearest plentiful source of builders' sand and gravel ballast for construction in the large and fast growing city of Winnipeg, its excavated sections are freshly and clearly exposed to view, with relatively little obscuration by falling talus slopes. The excavations now are several times greater than in 1887, when I first examined this gravel ridge, during my surveys of the Glacial Lake Agassiz. It then seemed to me exceedingly interesting and instructive, so that a small map, showing the esker and its vicinity, and a section along its earliest excavation, already reaching nearly three-fourths of a mile eastward from Birds Hill Station, were presented in my reports of that glacial lake.[2] But the observations made in August and September, 1909, on the British Association excursion, and in two later trips, have enabled me to learn the structure, geographic and geologic relationship, and the significance of this very remarkable esker far more satisfactorily than before.

Origin of the Name

A pioneer settler, Dr. J. C. Bird, widely known as a skillful physician, who lived many years in Saint Pauls township or parish, on the west side of the Red River, opposite to this hill, is commemorated in its name, which later was applied to the railway station when this first railway traversing Manitoba was built. Doctor Bird was elected a member of the first Legislature of Manitoba, in 1870; was speaker of the House from February 5, 1873, to the end of that Legislature, in 1874, and was reelected for Saint Pauls in the general elections of that year. He died in England in 1876.[3]

This dry, sandy esker ridge was often visited in the early spring and during the summer by Doctor Bird, and likewise by Hon. James W. Taylor, the United States consul in Winnipeg, 1870-1893, for gathering its wild flowers, including the pasque-flower, the earliest in spring, and many other species which are common on the esker but are rare or absent on the surrounding level and mostly clayey country.

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[2] Geological and Natural History Survey of Canada, Annual Report, new series, vol. iv, for 1888-89 (published in 1890), part E, pp. 38-40, with a section.
U. S. Geological Survey Monograph xxv, 1895, pp. 183-187, with map and section.

[3] History of Manitoba, by Robert B. Hill, 1890, p. 764.

Only one house has been built on the esker, this being the summer home of E. F. Hutchings, of Winnipeg, about 3 miles east from Birds Hill Station. The part of the esker there and for a half mile or more to the west, commanding a broad and beautiful prospect of the flat valley plain to the south and north, 50 to 60 feet below, was named Lorne Hill about 30 years ago, on the occasion of a visit by the Marquis of Lorne, Governor of Canada; but this name seems not to have come into general use. Instead, the earlier name Birds Hill, which originally was applied to the most western mile of the esker, separated by a lower part from its prominent development for more than a mile adjoining the summer residence of Mr. Hutchings, is now commonly bestowed on the whole length of this esker. Such usage of the name is promoted by the recent opening of a large excavation or pit by the Birds Hill Sand Company in the east end of the esker, from which the best grades of sand are obtained in large quantities for masons' use in mortar and plaster, and for the tempering of clay by the brickmakers of Saint Boniface and Winnipeg.

Structure of Birds Hill

Along the distance of almost a mile from its west end the esker rises to a height of 40 to 50 feet, and has an east-southeast course, with a width of a sixth to a quarter of a mile. Its central third or two-fifths, from near its crest northward, through a length of about 4,000 feet, has been removed for railway ballast, masons' use, etcetera, by steam shovels and by hand work, loading on cars of a spur branching from the Canadian Pacific Railway at Birds Hill Station. The elevation of the station is 759 feet, and of the crest of the ridge 800 to 810 feet, above the sea. On the southern side the section ranges from 30 to 50 feet in depth from the natural surface, and on the northern side from 20 to 25 feet.

As thus exposed to view, the greater part of this deposit is seen to be gravel, some of which is very coarse, containing pebbles and rock fragments of all sizes up to 10 inches or rarely 15 inches in diameter. Most of the pebbles and cobbles are well rounded, but some of the larger are angular, with only slight marks of water wearing. In some portions near the west end of this excavation no interbedding of coarser and finer layers of the torrential esker gravel is noticeable for 10 feet or more vertically, the spaces between the larger stones and cobbles being filled with finer gravel and sand. In the eastern half or two-thirds of the excavation, much sand and fine gravel are irregularly interbedded; and along a considerable extent toward its southeastern end a great part of

the section on the southern side, near the axis of the esker, consists mainly of sand, the depth of the pit there being 50 feet.

The stratification here and throughout all the 4 miles of the esker is approximately level, with occasional slight inclination eastward, but has frequent disturbed or confused portions adjoining either side and wherever very coarse gravel abounds. Torrential oblique bedding of the finer layers is frequent, any nearly horizontal layer 1 to 2 feet or more in thickness having often a secondary "flow and plunge structure," or cross-bedding, with dips from 10 to 30 degrees or rarely steeper, almost invariably inclining downward from west to east.

Paleozoic limestones make up about 75 to 90 per cent of the gravel, the remainder being Archean granites, gneiss, and schists; and such proportions are observed through the whole course of the esker. It is thus known, by evidence of the cross-bedding and of the sources of the gravel and sand, that this esker was deposited by a glacial river flowing eastward, deriving its drift from the part of the waning ice-sheet lying on the west, where limestone formations cover large areas.

Above the esker sand and gravel along this western mile a thin envelope of true till, mostly continuous at the top of the sections both on the south and north sides of the excavation, forms a most remarkable and instructive feature, which is presently to be fully described, with ensuing discussions of its significance concerning the amount of the drift that was englacial and finally superglacial, and in its bearing on the conditions of deposition of eskers.

Within the 22 years since my former observations here, this excavation has been widened, and it has been continued about 300 feet southward from its former eastern end. Then no considerable excavation had been made along the farther course of this esker eastward; but at the present time the aggregate removed from the eastern gravel and sand pits probably exceeds the amount thus far taken from the excavation already described, adjoining Birds Hill Station. About a quarter or a third part of the whole esker has been removed. At the same rate, disregarding its prospective increase on account of the present rapid increase of building in Winnipeg, this esker will be almost completely removed during the next 40 or 50 years.

Plate 31, the frontispiece of this paper, comprises a map and sections of this prolonged ridge, and of two noteworthy kames a few miles east and southeast, called Moose Nose and Oak Hummock, which are short and nearly round hills of similar material and origin as this esker. The map also shows associated gravel plateaus, ridges, and hills on the northeast.

Through its second mile Birds Hill, or ridge, is lower, having a height of 40 to 20 feet, declining southeastward, above the adjoining level areas, from which, with their productive farms, it is distinguished, like the higher mile at the west, by narrow but mostly continuous groves of small oaks and other trees and underbrush on the lower part of either slope of the ridge, while its rounded crest is a narrow avenue of prairie grasses and flowers, of species that prefer its dry, gravelly soil. The course of this part, crossing section 33, township 11 north, range 4 east, is from northwest to southeast; and the crest was occupied, until at some places fenced across in recent years, by a road for wagons, and long ago for Indian ponies and their trailing poles. The width of the ridge along this mile, from the foot of the slope on one side to that on the other side, varies from 60 to 30 rods, decreasing southeastward.

It is excavated only along a distance of about an eighth of a mile on its southwest slope, midway between the center and southeast corner of this section 33, for transportation by a railway spur track running to the south. The section there is wholly coarse gravel, nearly level in bedding, to the depth of 10 to 15 feet thus observed. No boulders were seen in this excavation, nor along all the trail or road running on the crest of the ridge for the mile and a half thence northwest, until, near the western end of the esker, the road descends along its southwest slope to the village of Birds Hill. In that descent for an eighth of a mile the roadway and the adjoining surface are strewn with boulders, mostly granitic, up to 3 feet in diameter, which belong to the envelope of till before mentioned.

At the southeast corner of section 33 the esker sinks to the lowest and most narrow part of all its course, rising only about 8 to 12 feet above the general level on each side; and for a short distance there, some 40 rods or more, its usual accumulation of gravel and sand is replaced, or is covered, by till with plentiful boulders. Perhaps this is a place where till overlies a diminished deposit of esker gravel; but it appears to me more likely that the esker deposit ceased there for a short space. Its place is taken by the low ridge of till, gently rounded up, with a width of about 30 rods or less, imitating in general form, but on a reduced scale, the esker whose continuation it represents.

Next eastward, in the south edge of section 34, this esker is again very prominent, taking a course from west to east. It has been excavated by the Canadian Northern Railway Company on a width of 300 to 500 feet for the distance of a mile through this section, the gravel and sand being loaded on cars of spur railway tracks here running west and thence south. The road on the south line of the section rises about 50 feet above the

general level, to the south edge of the top of the esker, which was somewhat flat and plateau-like for the width of 300 to 800 feet, while its southern and northern slopes add some 700 feet, making the whole width of the esker 1,000 to 1,500 feet, here having its most massive development.

The west half of this excavation consists of sand and gravel, mostly not very coarse, the pebbles in the coarser beds being from 4 to 6 inches in diameter, excavated to the depth of 10 to 20 or 25 feet, continuing still deeper on the north, but along the south line of the section seen to rest on till. In its east half the excavation is gravel and sand from 6 to 20 or 30 feet deep, underlain by till, which rises to a height of 30 to 40 feet or more above the general level, so that if the overlying esker deposit were wholly removed a broad ridge of till would be exposed.

About 800 to 1,100 feet west from the east line of this section 34, the north and lower side of the excavation showed a cut in the till 18 to 20 feet thick and 15 rods or more in length, also extending deeper. It is entirely free from evidences of water action, and contains frequent boulders 1 to 2 feet in diameter throughout its mass, not more plentiful at or near its top than below. Its whole thickness thus exposed is oxidized, having nearly the same yellowish gray color as the gravel and sand. The lack of larger boulders and their occurrence in no greater numbers at the top of the till deposit indicate that it was formed beneath moving ice, though probably thus amassed englacially, rather than by accumulation from superglacial drift, like many hillocks and ridges of marginal and interlobate moraines, which commonly are characterized by the abundance of boulders in and upon them. Coinciding in position with the broadest part of the esker, this exceptional mound or wide ridge of underlying till, rising high above the general level of the country, is almost surely attributable to conditions that produced both the prominent mass of till and the esker, in or beneath which it is a nucleal deposit.

On the north side of the west part of this Canadian Northern Railway excavation, the northern slope of the esker has been excavated along a distance of about a quarter of a mile by the Eli Sand Company, which also has large sand and gravel pits near Eli Station, some 30 miles west-northwest of Winnipeg. This cut, 10 to 25 feet deep and 10 to 15 rods wide, consists of coarse and fine gravel, with thin sand layers. The stratification, nearly horizontal, or dipping in some places 5 to 10 degrees east, is much broken by faults; and the beds are quite irregular, varying much in thickness within short distances, and having the coarse and finer layers confusedly interbedded. Cross-bedding is frequent, with the cur-

rent dips inclined 5 to 25 degrees eastward. No till nor boulders are encountered.

In the southwest quarter of section 35 the esker continues east to its end, near the middle of the east line of that quarter section. At the home of Mr. Hutchings and through the west half of the quarter, it has a nearly flat top, forming a plateau about an eighth of a mile wide, 50 to 40 feet above the general level, slightly declining to the east; and the gentle slopes to the south and north make the whole width about a third of a mile. Nearly all the surface is gravel and sand, with pebbles up to 6 or 8 inches in diameter; but about 20 rods southwest of Mr. Hutchings' house several boulders are seen, 2 to 4 feet long, which may belong to a projecting part of the nucleal till accumulation.

Narrowing eastward, the esker terminates as a rounded low headland near the center of the south half of section 35, half a mile east of the Hutchings residence. In its end the Birds Hill Sand Company has a pit 20 to 30 feet deep and about 100 by 75 feet in diameter, opened about a year ago. The upper 3 to 6 feet of the rounded eastward slope at the pit are gravel, partly coarse, with many cobbles up to 6 inches or partly 8 to 12 inches in diameter, nearly all being limestone. All the excavation below is sand, or has only scanty and fine gravel. The stratification is in part steeply inclined, with dips of 20 to 40 degrees eastward, as seen in one place for a vertical extent of 8 feet, so that it seems not to be merely cross-bedding. Some contortion of the inclined beds was noticed, but no faulting. The pit goes 10 feet below the general level, finding water which is curbed as a shallow well. No till nor boulders are there, nor in the near vicinity. The sand excavated is carried to Winnipeg by a branch railway that runs eastward to the southeast corner of this section 35, and thence passes south to the Canadian Pacific Railway.

Close at the south side of the railway track, an eighth to a third of a mile east from the pit, is a beach ridge of the Glacial Lake Agassiz, consisting almost wholly of fine sand, which has also been much excavated by the Birds Hill Sand Company. The beach sand forms a ridge extending from west to east, about 10 feet thick and some 20 to 15 rods wide, narrowing eastward, brought by wave erosion from the southern flank of the esker.

Adjoining the end of the esker, a nearly flat lower plain of sand and fine gravel, 15 to 10 feet above the general level, stretches a third of a mile to the north and a half to two-thirds of a mile northeast and east. Next northeastward beyond this plain, in the central part of the northeast quarter of this section 35, is a somewhat rounded hill 20 to 40 feet

high, consisting of sand and gravel on its southern slope, but of till on its top and northern slope, with many boulders up to 5 feet in diameter.

Till overlying the Esker Gravel and Sand

The most extraordinary feature of this esker is the envelope of till covering its western quarter, along the course of the great excavation first described, reaching nearly a mile east from Birds Hill Station. In the excursion of the geologists attending the British Association, this overlying till, first observed, as I think, by J. B. Tyrrell, of Toronto, Canada, was clearly seen by all the party, including several British geologists, others from Canada, and, among United States geologists, Frank Leverett and Frank B. Taylor, experts in all phases of glacial, fluvial, and lacustrine action.

Here I must make a confession and apology. That this most significant feature of Birds Hill was not observed by me in my former field work, and therefore was not described and delineated in my reports published in 1890 and 1895, was doubtless due to the thinness of the till sheet and its yellowish gray color, similar to all the esker gravel and sand.

The section and description given by me in those reports, however, especially mention a mass of till seen inclosed within the esker, of which I wrote:

> "Imbedded in this coarse gravel on the south side of the excavation I noted a mass of ordinary till, unstratified boulder-clay, inclosing gravel and boulders in a solid matrix of somewhat sandy clay, wholly bounded by definite but irregular outlines, its dimension vertically being about 10 feet and its length 20 feet. . . . It probably was derived from the drift that was contained within the ice-sheet and finally overspread its surface when the greater part of the thickness of the ice was melted. From a sheet of drift thus deposited on the ice that formed the bank of the glacial river this mass may have fallen into its channel."

No similar inclosed mass of till was seen in the sections examined last summer and autumn; but I believe that the till mass seen in 1887 and thus described was in its original position as imbedded in the esker by falling from above while the gravel ridge was being accumulated, rather than as a part of a talus fallen from the gravel and sand beds and from the overlying till sheet on account of their being undermined by the excavation.

Boulders occurring in considerable numbers over the northern slope of this part of the esker and left where the gravel and sand had been excavated, I endeavored to explain in the former reports as follows:

"Some two hundred boulders were found scattered upon the area of the excavation; and they occur with nearly the same frequency on other portions of this northern slope of the hill, but are rarely found on its top and southern slope. They vary in size from 2 to 8 or 10 feet in length; nearly all are Archean, but a few of Paleozoic limestone, up to 5 feet in length, were observed. None was seen inclosed within the gravel and sand of the esker, and the workmen informed me that they occur only on or near the surface. This hill was covered by Lake Agassiz, and its boulders were doubtless dropped or stranded from bergs and floes on this lake before the border of the ice-sheet had retreated from the vicinity. Indeed, the occurrence of the boulders chiefly on the northern slope seems to indicate that they were mostly stranded there while ice yet remained beneath this deposit and prevented its entire submergence in the lake."

Details of the esker section and the overlying till on the deeper south side of the excavation are as follows:

From its west end this section has a thin covering of till, with frequent boulders 2 to 5 feet in diameter, for a distance of about 350 feet. In the east half of this extent the till varies from 2 to 8 feet in thickness, being thickest near its east limit, where it ceases by the rising of its lower boundary at an angle of about 45 degrees to the surface. Above the till along most of this extent, excepting where it comes to the surface at the east, is a thin surface deposit of gravel 1 to 3 feet thick. The till is underlain by the very coarse water-worn esker gravel, obscurely and confusedly bedded, 10 to 20 feet thick and continuing below the excavation.

About 5 to 10 feet east from the limit of the till is a sand mass, 3 by 6 feet in dimensions, lying 2 to 6 feet below the surface, wholly inclosed in the coarse gravel, being perhaps a frozen mass there imbedded while the gravel was rapidly deposited around it.

Through the next 100 feet east the section is mostly very coarse gravel, not distinctly bedded, with pebbles and cobbles up to 8 inches in diameter, well water-worn, and also inclosing occasional partly or wholly angular rock fragments up to 18 inches in diameter, from the surface downward, seen to the depth of 20 feet. In that part, between 30 and 60 feet east of the limit of the till before noted, the gravel incloses an irregular inclined layer of sand, 6 inches to 3 feet thick, beginning at the surface and running downward to the east 12 feet in its length of 30 feet. This is the only exception to the coarse gravel otherwise making all that part of the section.

Next east for 75 feet the section, 20 to 25 feet deep, is finer gravel, with pebbles up to 4 or 6 inches in diameter, containing no unworn larger fragments; but there it is capped by a stratum, 2 to 5 feet thick,

of very bouldery gravel containing subangular rock fragments up to 2 or 3 feet.

In the next 200 feet the envelope of typical till, beginning with similar abruptness as it ended, is continuous, varying in thickness from 10 to 3 feet. Three times in the distance of 200 feet it suddenly thickens downward to about 10, 7, and 8 feet respectively from west to east, and thins more gradually east from each bulge. Its top throughout is nearly level, forming the surface eastward, and overlain by a surface gravel westward, which gradually thickens to 3 feet. Under the till the lower part of the section is rather fine gravel, seen to the thickness of 20 feet, having worn pebbles up to 3 or 4 inches and no larger unworn stones. In some parts the gravel is sparingly interbedded with sand layers 6 to 18 inches thick. The stratification is continuous, though partially dim, with gentle dips of 5 to 15 degrees eastward, and displays no faulting nor disturbed bedding.

Thence a continuous layer of the same typical till, having no trace of stratification, extends about 500 or 600 feet east. It is 4 to 8 feet thick, and contains frequent rock fragments and boulders, nearly all of unworn angular forms, up to 3 feet in diameter. Except for a distance of several rods at the west, where it is the surface, the till is overlain by a surface deposit of very coarse gravel, 1 to 3 feet thick, containing rounded cobbles up to 12 and 18 inches. The till is underlain continuously by such quite fine gravel as was seen in the adjoining distance of 200 feet west, 20 to 25 feet thick in the excavation and continuing below, having pebbles from 1 to 4 inches in diameter in its various beds, but no clear sand. The stratification, often dim, nowhere faulted, is partly level, but mostly dips 5 to 10 degrees eastward.

At the east end of the part thus described, the till ends by being merged or gradually changed, within a distance of 20 to 40 feet, into coarse, well bedded gravel, which contains cobbles up to a foot or 15 inches in diameter. This deposit forms the upper 8 to 12 feet of the section for the next 300 feet east, and is underlain by fine gravel into which the excavation goes down 25 to 30 feet. Numerous layers in the lower part, 6 to 18 inches thick, are almost wholly sand. The stratification of the fine gravel and sand is nearly horizontal, or dips in some portions 5 to 8 degrees to the east; but occasionally the deposit for thicknesses of 2 to 6 feet has no definite stratification lines.

Farther east and southeast, for about a third of a mile, in the curving course of the excavation, including at its end the extensive pit lately abundantly worked by the engineering department of the city of Winnipeg, all the section on the southern and southwestern side, 40 to 50 feet

deep, is good gravel and sand. Its coarser layers commonly have pebbles 3 to 5 inches in diameter, with no larger stones nor boulders and no till. Some layers are chiefly sand, with scanty gravel, and rarely a bed 1 to 2 feet thick and 50 to 75 feet long is almost clear sand.

Returning to the west end of this long excavation, near Birds Hill Station, and examining the section along its lower northern side, we have for a distance of about 2,000 feet a continuous mantle of till, 6 to 10 feet thick, mostly typical unmodified glacial drift, with frequent boulders in and upon it, but in some parts showing modification, as slight stratification and assorting by water action. The till and boulders make the surface, or through perhaps half of this distance are thinly covered by a coarse surface gravel, 1 to 3 feet thick. Beneath the till the esker gravel, excavated continuously for a thickness of 10 to 15 feet and reaching lower, has usually pebbles from 1 to 3 inches in diameter, and in some parts up to 6 inches, all water-worn, with no larger stones nor boulders. It is nearly levelly bedded, but frequently dips 5 to 10 degrees to the east.

The till terminates at the east end of the part thus noted, there being the surface and 8 feet thick, by an abrupt ascent of its lower boundary at an angle of 70 degrees with the horizon, and is succeeded by fine gravel, which immediately to the east forms all the section, exposed to a depth of 20 feet.

Within about 50 feet onward the till begins again, and it soon thickens to 6 or 8 feet, its lower boundary being inclined at first 15 to 20 degrees. When it has thus attained a depth of about 8 feet, it runs as a surface deposit 6 to 10 feet thick, or in large part is covered by 1 to 3 feet of coarse gravel, for nearly 1,000 feet. It is underlain, as westward, by fine gravel and sand, excavated to the thickness of about 15 feet, nearly levelly stratified. This stretch of the till envelope ends somewhat like the preceding, but less suddenly, tapering out from a depth of 10 feet by the ascent of its under edge to the surface at an angle of 25 degrees.

After a second interval of only 50 feet, in which the fine esker gravel comes to the surface, the coating of till is renewed and has a depth of 5 to 10 feet at the surface, or with a few feet of coarse gravel over it, as before, for the next 500 feet, curving to the southeast and south. It terminates near the end of the excavation, where in the Winnipeg City pit the whole section is again fine gravel and sand, excavated 50 feet in depth from the surface at the crest of the esker.

Formation of the Esker by a Glacial River

Independently of each other and near together in time, the origin of eskers and kames through deposition by ice-walled rivers, small or large,

flowing from the melting ice-sheet, mostly in its waning stages at the end of the Glacial period, was thought out and published by D. Hummel and N. O. Holst in Sweden and Prof. N. H. Winchell and the present writer in the United States.[4]

Along the course of this gravel and sand ridge of Birds Hill a stream poured from the glacial melting and attendant rains, walled on each side by yet remaining tracts of the retreating continental ice-sheet, which gradually rose to greater heights westward and northward. The very plentiful limestone pebbles and the slight easterly dips of many portions of the esker beds demonstrate that this small river flowed southeast and east.

Wherever belts of marginal moraine hills or low hillocks and ridges are typically developed, as they have been traced and mapped continuously across more than half of our continent, from Cape Cod and Long Island to the northwestern plains of Alberta, with much interlocking and wide diversity of topographic expression and drift material, these moraines always include, within any district of much extent, considerable accumulations of stratified gravel and sand, frequently amassed separately from the marginal till and boulders, so that they form kames, that is, low mounds and knolls or sometimes prominent hills, and occasionally eskers, which are prolonged kames, associated with the other and more strictly moraine hills of till.

Birds Hill and the contiguous kames, Moose Nose and Oak Hummock, may be referred in general to glacial streams temporarily existing at some time during the stage of the receding ice-sheet when the Itasca moraine in Minnesota was heaped along its boundary; but on the area of Lake Agassiz all the moraine belts that cross it are indistinctly or quite interruptedly recognizable. These fluvial hills of gravel, with overlying and underlying till, are the most noteworthy drift accumulations that are found in the probable course of the Itasca moraine on this lacustrine area.

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[4] The early studies of Hummel and Holst, in 1874-1876, on the eskers of Sweden, where this class of drift formations has more extensive development than anywhere else in the world, are cited by Prof. James Geikie in "The Great Ice Age," second edition, 1877, pp. 414, 415.

N. H. Winchell: Geological and Natural History Survey of Minnesota, Second Annual Report, for 1873, p. 194.

Warren Upham: On the origin of kames or eskers in New Hampshire. Proceedings of the American Association for the Advancement of Science, vol. xxv, for 1876, pp. 216-225; Geology of New Hampshire, vol. iii, 1878, pp. 12-14.

Consult also the U. S. Geological Survey Monograph xxxiv, 1899, The glacial gravels of Maine and their associated deposits, by Prof. George H. Stone, treating of the region having the longest and most abundant eskers in North America.

Deposition of the overlying Till

In the sections examined on the south and north sides of the excavation near Birds Hill Station, described in the foregoing pages, the extensive but partially interrupted sheet of till above the main esker gravel deposit has only the usual proportion of boulders ordinarily belonging to the till of this region, nor are they of larger size and less worn and striated than is their usual condition elsewhere in the surrounding general drift sheet. At least two or three hundred large boulders, however, from 3 to 10 feet in length, have been found during the progress of this excavation, in and upon the overlying till.

About the west end of the esker such large and unworn boulders are more abundant, as is characteristic of marginal moraines, strewing the surface plentifully where the west foot slope of the ridge is crossed by the road leading north from Birds Hill village, and also on the southwestern slope where the road or trail descends from the crest to this village. They similarly abound again a mile farther east, on the lower part of the northeastern slope, within an eighth of a mile eastward from the deep Winnipeg gravel pit, which is the end of the excavation.

But along the crest of the esker, close above and south of the section noted at the south side of the excavation, no boulders are seen, nor on the greater part of its southward slope, the whole depth of the esker there being probably gravel and sand. Nor was any boulder observed imbedded in the sand and gravel beds in any part of the very extensive sections shown on both sides of the excavation, either at my visit in 1887 or last summer.

The best explanation, as I believe, for the mode of deposition of the till above the esker gravel is to refer it to a moderate re-advance of the front or wall of the ice-sheet from the northern side of the esker channel, carrying some of its englacial and finally superglacial drift over the northern flank and west end of the esker ridge after that part of the gravel and sand deposit had been laid down in a somewhat wide channel open above to the sky. While the till was thus being spread over the north slope and west end, the continued deposition of stratified drift by the esker stream may have been adding to the thickness of its axial portion, raising its crestline above the till-covered northern slope.

In the halting and partly readvancing and wavering stage of the ice-border when any marginal moraine was accumulated, many of its kames were probably more or less covered with till and boulders; but the occurrence of a till envelope or mantle upon an esker is very rare. The observations here recorded for Birds Hill are perhaps the most remarkable

in this respect that have been made known in the extensive literature of glacial geology.

Apparently a readvance of the ice-front from the north and west to an extent of about 1,000 feet beyond its former place, along this distance of about 1 mile, satisfactorily accounts for these sections of till above the esker gravel and sand. Such oscillation of the ice-wall required possibly only two or three summers, but more likely the summers of a decade, more or less, averaging a little cooler than the preceding and following years of relatively rapid wane and withdrawal of the ice-fields at the end of the Glacial period. The thin gravel beds at the surface above much of the till sheet may have been formed a few years later, when the previously onflowing border of the ice was melting away.

In passing we may add that the whole duration of Lake Agassiz in this basin of the Red River and Lake Winnipeg, with retreat of the ice boundary across the 1,000 miles from western Minnesota to Hudson Bay, appears to have measured only about a thousand years, as estimated from the amount of its wave erosion and beach sand accumulation, in comparison with the much greater amount of similar work done by Lake Michigan and others of the Great Lakes of the Saint Lawrence Basin since the Ice Age. As a very small part of that time of duration of the glacial lake and departure of the ice-sheet from its area, we may reasonably infer that the time occupied in the accumulation of the kames and esker near Winnipeg must have been short, probably not exceeding 20 or 30 years.

Depth of the Esker shown by Wells

To provide water for the workmen in the excavation, a well 45 feet deep had been dug or bored at its bottom about a half mile from Birds Hill Station before my visit in 1887. It was wholly in the same formation of gravel and sand, showing for this deposit there a thickness of about 90 feet below the crest of the esker, or some 40 or 50 feet below the general level of the flat valley plain.

Again, about a third of a mile farther east a second well, recently dug or bored for the workmen of the Winnipeg pit, goes down below that pit 40 feet in the same stratified drift to water. Like the preceding well, it gives a depth of 90 feet for the esker deposit. The important and very significant feature thus proved is that the fluvial gravel and sand continue about 40 feet lower than the level of the surrounding country. As will be more fully explained on later pages, this implies that a very large part of the general drift-sheet was material contained in the ice-sheet, borne along by it above the subglacial land.

Neil J. McGregor's well in Birds Hill village, about 15 rods southwest from the edge of the esker ridge near its west end, bored last summer, has this section: Soil, 1 foot; bluish till, with few boulders, 11 feet; gray till, 8 feet; coarse gravel, all water-worn, with nearly all the cobbles limestone, very abundant, 1 to 10 inches in diameter, 40 feet; less coarse gravel, or more probably till, with only few stones, 10 feet; limestone, the bedrock, 28 feet, to the bottom of this well, at 98 feet, whence water rises in the well pipe 70 feet, to 20 feet below the surface.

Here we may think that an englacial tunnel, occupied by a torrent that had fallen through crevasses and moulins of the ice, thence flowing through this tunnel to join the esker river, became filled with the torrential gravel, similar to that chiefly forming the west end of the esker. The bottom of the coarse gravel in this well is at a depth of 60 feet from the surface, being somewhat lower than the bottom of the wells in the excavation. The bluish gray color of the till, extending to the surface, is due to its relatively unoxidized and unleached condition, in contrast with the yellowish gray till of the esker, where its height above the adjoining land has permitted infiltration of the water of rains, favoring the change of its iron element from the protoxide combinations to the rust-coloring sesquioxide. The same bluish gray till forming the surface is seen at the post-office kept by George Chudleigh, at the school-house, and indeed in all the cellars and wells of the village.

Relationship to the Glacial Lake Agassiz

If the overlying till in Mr. McGregor's well, having a thickness of 20 feet, represents an average of the amount of englacial till above the level in the ice-sheet at which the esker was formed, the total quantity of englacial drift was apparently equal to a thickness of 30 feet or more, some two-thirds of it being held and carried along higher in the ice than the highest level of Lake Agassiz here, which was about 500 feet above the present land surface.

Much of the interest of this subject depends on the relation of Birds Hill to Lake Agassiz. The esker is situated near the center of the area of the ancient glacial lake. On the east border of its area the Herman Beach, the earliest and highest of a series marking the boundaries of the old lake, is mapped from the southward outlet at Browns Valley, Minnesota, in its course north and northeast to the vicinity of Red Lake, being there 1,210 to 1,215 feet above the sea; and on the west it extends through North Dakota and onward across the Assiniboine River to Riding Mountain, west of the south part of Lake Manitoba, there lying at an altitude of 1,300 to 1,320 feet above the sea.

It is thus evident that when the ice-sheet had so far receded that its border was being melted away in the vicinity of Birds Hill, permitting the esker to be formed by a stream flowing from it, the level of the ice-dammed lake there, about midway between Red Lake and Riding Mountain, was about 1,260 feet above the sealevel. Comparing that height with the surface at Winnipeg, 757 feet, at Birds Hill Station, 759 feet, and the level of Lake Winnipeg, 710 feet, we see that the ancient Lake Agassiz was 500 feet deep above the site of Birds Hill at the time of formation of this esker, the lake then being at its earliest and highest stage.

Further, it seems to me quite surely demonstrated by the described characters of the stratified drift forming this esker of Birds Hill, that its deposition took place from a freely running stream in a channel that was inclosed on the sides by walls of the waning ice-sheet and was open above to the sky. It was not deposited in the still water of a deep lake, between channel walls of ice rising from the land surface; for then the esker gravel and sand and the frontal lower plain adjoining the east end of the esker could not have been spread out as they now are found. Fluvial currents, such as could only exist above the surface of the adjoining Lake Agassiz, brought and laid down the modified drift of the ridge and its terminal plain. Afterward, by the completion of the melting and retreat of the ice-border here, on each side and beneath the esker and plain deposits, they were allowed to sink gradually about 500 feet, until they rested on the land.

A short summary of the history of Lake Agassiz needs to be added. Beginning as a small lake at the southern end of the wide Red River valley outflowing to the south in a channel where Lakes Traverse and Big Stone now are, it grew in length northward with the recession of the ice-sheet which was its barrier. Beyond the limits of my explorations of its shorelines, passing through Minnesota, North Dakota, and southern Manitoba, north to the Riding Mountain, its farther extent northward, by Riding and Duck mountains and the Porcupine and Pasquia Hills and across the Saskatchewan River, has been explored by J. B. Tyrrell for the Canadian Geological Survey. Its length grew to at least 700 miles, and its area doubtless exceeded 100,000 square miles, surpassing the combined areas of the Great Lakes tributary to the Saint Lawrence.

After the formation of the uppermost or Herman beach, a series of several lower beaches with outflow still to the south was formed by the downward erosion of the channel of the outflowing river. Still later a large series of yet lower beaches recorded the successive lower outlets of the lake while it outflowed northeasterly, previous to the full melting

of the central part of the ice-sheet. Finally the area crossed by the Nelson River and the basin of Hudson Bay were uncovered, allowing the glacial lake to be wholly drained away, excepting its present representatives, Lakes Winnipeg, Manitoba, and Winnipegosis, lying in hollows of the land.

Meanwhile, through the greater part of the time of existence of Lake Agassiz, this part of the earth crust, unburdened by the melting of the thick and heavy ice-sheet, was gradually rising, and its greatest uplifting took place in the central part of the formerly ice-covered area. Thus the successive early shorelines of Lake Agassiz were much uplifted, with all the lake basin, most in the central region of the continental glaciation, and least about its boundaries. This continental uplift gave to the highest and oldest shore a northward ascent that averages nearly a foot per mile for 400 miles from the southern mouth of the glacial lake. Its lower and later shores are each less inclined than the preceding, until the lowest beach is scarcely changed from its original horizontality, showing that the great uplift of this lacustrine area was practically completed before the ice-barrier on the lower part of the course of the Nelson River disappeared.

A part of a very sandy beach ridge of Lake Agassiz adjoining the east end of this esker has been much excavated for the use of its sand by the Birds Hill Sand Company, as before noted.

Again, about a mile and a half west from that place a more typical but smaller beach ridge is crossed by the roads on the north and east lines of section 28, township 11 north, range 4 east, about 2 miles southeast of Birds Hill Station. This beach, running from northwest to southeast, crossed by each road about 20 rods from the northeast corner of this section, is excavated to depths of 3 to 5 feet at the roadside, and is seen to be fine gravel and sand. Much of the beach deposit consists almost wholly of pebbles from 1 to 3 inches in diameter. It is a very low, gently rounded ridge, about 4 to 6 rods wide, elevated at its crest only 3 or 4 feet above the land adjoining its northern side, which is close to the depressed and till-covered part of the esker's course. The southwestern and lakeward side of the beach ridge has a descent of some 5 or 6 feet in 3 or 4 rods, to the edge of the very slowly declining flat lowland of till next south, where the lake at the time of its accumulation of the beach had a depth of 2 to 5 feet.

Both of these beach deposits, observed only for short distances, probably belong to the lowest or Niverville stages of Lake Agassiz, represented near Niverville, Otterburne, and Morris, south of Winnipeg, by small beach ridges, 2 to 4 feet high, whose crests vary from 777 to 784 feet

above the sea. Exact leveling from Birds Hill Station seems desirable to ascertain the heights of these shorelines. Until this test shall be applied, I think the eastern sandy beach to be at or near 780 to 785 feet, and the western and less conspicuous beach probably several feet lower.

Other Esker and Kame Deposits in the Vicinity

Township 12 north, range 5 east, from 4 to 12 miles east and northeast of Birds Hill Station, has numerous esker ridges, shorter hills, and extended plateaus of gravel and sand, from 50 to 100 feet above intervening swamps, parts of which are well wooded with spruce and tamarack. The uplands, forming plateaus, eskers, and kames, are largely prairie, but in some tracts are scantily wooded with scrubby oaks, elsewhere with a better growth of poplars, and eastward have a few white pines.

One of the most conspicuous of these elevations, as viewed from the west, is called Griffiths Hill, on the township plat in the Dominion Lands Office at Winnipeg, drafted in 1872 from the original surveys. The top of this hill, in the northeast quarter of section 19, is about 875 feet above the sea, or a little more than 100 feet above the railway, 2 miles distant on the west.

The whole group is composed of gravel and sand, and the topographic forms indicate deposition by glacial rivers near their mouths, where they flowed between walls of ice, being here and there divided by ice-islands, whose melting left the hills, ridges, and plateaus bounded by moderately steep slopes. With the completion of the melting of the ice about and beneath these deposits, they sank to the bottom of Lake Agassiz. Toward the north, west, and southwest they border on the flat plain of the Red River valley, 750 to 760 feet above the sea, while toward the east and southeast they are connected with plains and undulating tracts of gravel and sand which extend with slow and gradual ascent to the Lake of the Woods and into Minnesota.

About 2½ miles east from the east end of the esker of Birds Hill is the Moose Nose, a conspicuous rounded hill, mainly composed, so far as can be seen on the surface, of modified drift—that is, the gravel and sand brought and deposited by a glacial river. This massive kame covers an area about two-thirds of a mile in diameter, in the west part of section 29 and the east half of section 30, township 11 north, range 5 east. The kame deposit surmounts a larger somewhat elevated oval area of typical till, which comprises most of the eastern two-thirds of section 30 and continues south in the north half of the northeast quarter of section 19,

rising by very gentle slopes to the height of 25 to 40 feet above the general level of the flat surrounding country. With steeper slopes the kame rises to a flat or moderately undulating top, which may be called a plateau, 70 to 80 feet above the same level, having an area of 50 acres or more.

In addition to its basal tract, till may also form a nucleus of the higher kame; for beside the road on the line between sections 29 and 30 an excavation 5 to 6 feet deep, near the top of the southern slope, is in part true till, which is seen to a thickness of 4 feet and continues lower. Thence for an eighth of a mile north, on the highest part of the road, and for 500 feet or more east and west from the road, granitic boulders up to 5 or 6 feet in diameter are frequent in and on the sand and gravel that form the surface, probably belonging to an underlying till very thinly veneered with modified drift.

Sunnyside Cemetery, on the highest eastern part of this kame plateau, has an extensive view for several miles eastward and southward; but toward the west a far view is prevented by the low oak woods with which the kame is covered, except clearings of a few acres designed for cultivation but abandoned because of their gravelly and sandy soil.

On its east border the kame deposit of the Moose Nose has been extensively excavated for ballasting the Canadian Pacific Railway, being removed by a branch line running south. The whole excavation, a quarter of a mile long, from 10 to 200 feet wide, and exposing a section 25 to 40 feet deep, consists of gravel and sand, which continue lower, with no till nor even a single boulder. About a fourth part is clear sand, in layers up to 2 feet thick; the other three-fourths are gravel, varying in coarseness to occasional layers holding cobbles up to 8 or 12 inches in diameter, or quite rare up to 18 inches, all well water-worn. Nearly all the pebbles and cobbles are limestone. The stratification is horizontal, with infrequent cross-bedding, which, wherever observed, dips a few degrees to the east. All the section is very definitely stratified, and it has no fault lines nor places of confused or obscured layers.

Oak Hummock, in the southeast part of section 12, township 11 north, range 4 east, also extending a third of a mile east into section 7 of the next township, lying thus 3 miles south of the Moose Nose, has nearly as great area but less height, rising only 45 to 50 feet above the surrounding level. It has an oval outline a mile long from west to east and two-thirds of a mile wide. This hill consists mainly of kame gravel and sand, but has an underlying rounded accumulation of till, which rises to a height of about 30 feet, or two-thirds as high as the kame deposit.

A shallow but long cut across the northern side of this hill has been

made on the course of the electric power line that brings power from Lac du Bonnet to Winnipeg, passing from east to west through the center of these sections 7 and 12. The cut, made to supply ballast to the Canadian Northern Railway by a track running west, is a half mile long, extending through the east half of section 12, and is only 5 to 8 feet deep; but as the railway grade rises some 25 feet above the general level, the top of the cut is at the height of 30 feet or more. The west half of the cut is very coarse gravel, nine-tenths of it consisting of pebbles and cobbles from a half inch to 8 inches in diameter, of which fully 95 per cent are limestone, the others being mostly granitic. The formerly steep sides of the excavation had mostly fallen down at the time of my visit last September, so that the stratification was visible only for a small part, there showing dips of 5 to 30 degrees east.

The underlying till rises with a very gentle and smooth slope beneath the east part of the gravel, and forms the surface onward for about an eighth of a mile, along the eastern quarter of the cut, or is in part overlain by a surface stratum of the coarse gravel 1 to 2 feet thick. It contains plentiful rock fragments and boulders, up to 3 feet in diameter, most of the large boulders being granitic, while nine-tenths or more of the small fragments are limestone. As in the Moose Nose and Birds Hill, the stratification of the gravel and the material of both the gravel and till denote derivation from the west.

On the township line road crossing this Oak Hummock from north to south, the surface is till from the east end of the cut for some 30 or 40 rods south; but the higher part of the hill, rounded and somewhat irregularly rolling in contour, consists of gravel and sand, without boulders. It is mostly wooded with poplars, scrub oaks, and bushes; but it has two small cleared fields which were formerly cultivated. An excavation near the southeast corner of the northern field, about 100 feet in diameter and 6 to 10 feet deep, is all coarse gravel, nearly as in the railway cut.

How confluent currents of the ice-sheet heaped the till in its prominent underlying and nucleal accumulations which form parts of Oak Hummock, the Moose Nose, and the east half of Birds Hill will here receive no attempt for explanation, other than to indicate that the glacial movements thus amassing the till were closely related with the contour of the ice surface which immediately afterward caused an ice-walled river to bring and deposit in these places the sand and gravel of the kames and esker. Further study may be profitably given for ascertaining the conditions of drift transportation and deposition by which these till accumulations were formed, and they may contribute light on the difficult question of the origin of drumlins.

In the general northward recession of the glacial boundary, its strong frontal currents of the ice heaping a part of its till, and closely succeeding exceptionally large fluvial deposits, formed earliest the Oak Hummock, next the Moose Nose, and latest Birds Hill, though probably no long intervals divided the times of their formation.

Where the boundary of the ice-sheet lay eastward of Birds Hill at the time of its slight readvance which spread till and many boulders over the western part of that esker is perhaps indicated by the abundance of boulders on the surface of the till forming the top and north slope of the low hill in the northeast quarter of section 35, township 11 north, range 4 east, before described in connection with the east end of the esker, which is three-fourths of a mile distant to the southwest, in the southern part of the same section. A half to three-fourths of a mile farther northeast, in the south part of section 1, township 12 north, on the cleared course to be occupied by a new line of transmission of electric power, very abundant boulders are similarly found on the northwestern end of a wooded ridge, 50 to 75 feet high. Eastward this ridge is probably an esker, and after an extent of about a half mile to the southeast and east it widens into a prairie plateau or plain, composed of modified drift, reaching northeast and east 2 to 3 miles or more, and having a height 75 to 100 feet above the extensive level lowland on the south.

Nearly all the plateau has a surface of gravel and sand, but about 2 miles east-northeast from the very plentiful boulders noted in section 1, a tract of several acres, distinguished from the general prairie by its scattered small oaks, has many boulders up to 6 feet in diameter, both of granite and limestone. The surface there on a small area thus appears to be marginal till, though not differing much in height or contour from other parts of the general plain of modified drift. This place is close east of the most western of several lone white pines, the first seen in going eastward from the Red River valley.

Connecting these places of unusual profusion of boulders, we have a course of about 7 miles marked interruptedly by one of the most characteristic features of marginal morainic drift. Therefore we may perhaps rightly picture in our minds a steep frontal ice slope or cliff extending along that distance from the site of Birds Hill Station to the lone pine and scrub oaks, readvancing a few hundred feet and depositing its boulders so plentifully in these several places.

Belt of modified Drift extending Southeastward

Modified drift, consisting of stratified gravel and sand, with local deposits of clay, overlies the bedrocks and the till, and generally forms the

surface, on an extensive area stretching from the vicinity of Birds Hill southeasterly to the southwest part of the Lake of the Woods and to the Rainy River, and continues on large tracts in Minnesota, to the lakes at the sources of the Mississippi and to the Leaf Hills, and thence southeastward to Minneapolis and Saint Paul. The contour of the greater part of these deposits, through their extent of 400 miles, is flat or moderately undulating, and their surface varies in height from a few feet to 50 feet or rarely more above the adjoining lakes and streams. In central Minnesota these tracts of gravel and sand have an elevation that increases from south to north, being 825 to 950 feet above sealevel in the vicinity of Minneapolis and Saint Paul, rising gradually to 1,200 feet in the distance of about 100 miles northwest to Brainerd, and ranging from 1,350 to 1,500 feet between the Leaf Hills and Itasca Lake. Thence their surface sinks to 1,150 and 1,075 feet in the vicinity of Rainy River and the Lake of the Woods, and is between 750 and 875 feet in the district here especially described, northeast of Winnipeg.

On each side this broad belt is bordered by areas of nearly the same general elevation, which have mostly a surface of till; and it is to be remarked that the heights of the tracts of modified drift and till are alike determined by that of the underlying rocks on which these superficial deposits are spread as a sheet of slight depth in comparison with the gradual change in their elevation. The drift-sheet on this belt, including both the sand and gravel and the underlying deposits of till, probably varies in its average thickness from 50 to 150 feet, while its central portion rises 400 to 600 feet above its south and north ends.

The distribution of the modified drift thus found on large tracts along a wide belt from Saint Paul to Winnipeg, while it is very scantily developed on a still wider region of Minnesota, North Dakota, and Manitoba southwest of this belt, and likewise is scanty or wanting on its northeast side in northern Minnesota and about Rainy Lake and the northeast and north portions of the Lake of the Woods, seems to be attributable to converging slopes of the surface of the ice-sheet and the consequent convergence of its currents, which brought an unusual amount of englacial drift into the ice along this belt, and by which also the streams produced in its melting were caused to flow thither from extensive tracts of the ice on the east and west. The glacial striæ of these adjoining areas show that on the east the course of the motion and the descent of the surface of the ice-sheet were from northeast to southwest, but that on the west the glacial currents moved and the ice surface sloped toward the southeast.

Drift limestone is absent or very rare on the east, because no limestone formations were crossed within several hundred miles by that part of the ice-sheet; but on the west the drift, consisting chiefly of a thick sheet of till, contains much fine limestone detritus, sand and gravel, and frequent boulders of limestone, borne southeastward from Manitoba over the Archean area of the southwest part of the Lake of the Woods, of Rainy River, and of northern and central Minnesota. In the same directions with the slopes of the ice surface, which are known from the courses of the glacial striæ and the transportation of the drift, the streams of the glacial melting flowed convergently from the east and west, from the ice over northern Minnesota and eastern Manitoba on one side, and from that over the Red River valley and western Manitoba on the other, toward this belt of plentiful superficial deposits of gravel and sand.

Evidence of much englacial and superglacial Drift

The chief reason for the detailed descriptions presented in the foregoing pages is my wish to have other field workers and theorists in glacial geology come to my point of view and conclusions, that a great amount of drift was contained in the lower part of the ice-sheet, was carried along with its motion, and during the final melting became superglacial when the upper part of the ice melted away. The esker deposit of Birds Hill is shown by the wells in and near it to extend 50 or 60 feet below the general level of the Red River Valley plain, to a depth only 10 feet above the limestone bedrock. Seeing that the esker gravel and sand were originally deposited, as before shown, at or above the level of Lake Agassiz, which in its earliest and highest stage here, at the time of this esker river, was 500 feet above the land surface, I must conclude that the englacial and later superglacial drift of the ice-sheet here above that level amounted to about 20 feet, the thickness of the till above the coarse gravel in Mr. McGregor's well.

Beneath the level of the glacial lake, in the lower 500 feet of the ice-sheet, the quantity of englacial drift seems to have given a thickness of 10 feet, if we thus consider the entire drift deposit beneath the coarse gravel in this well, attributing none of it to subglacial deposition.

As the surface at the well is 6 or 8 feet above the general level of the adjoining valley plain, its depth of 70 feet to the bedrock indicates that the general sheet of the drift and lacustrine and alluvial beds together averages 60 feet in thickness in this vicinity. From my observations of till at or near the surface of the valley plain in many tracts about Birds Hill and Winnipeg, and elsewhere along all the length of the Red River

valley, the amount of lacustrine sedimentation appears to have been slight and even negligible, excepting on areas of deltas where the lake received tributary streams laden with modified drift. Most of the stratified clay and silt along the axial lowest part of the valley, as about Birds Hill, seems therefore referable to alluvial deposition by river floods after the glacial lake had been drained away. Both lake sediments and river alluvium are absent from the tracts of till, indicating there for the till alone a probable thickness of 50 or 60 feet. On other areas, where the alluvium is deep, as generally along the central part of the valley, quite probably the underlying till averages likewise some 50 feet in thickness, nearly all of which, according to the evidence afforded by Birds Hill, was englacial and finally superglacial.

The distance from Birds Hill to the boundary of the glacial drift is about 700 miles to the south and 300 miles to the southwest. It may be estimated, from altitudes of the drift on the White Mountains, the Catskills, and the Adirondacks, that the ice-sheet similarly rising over Manitoba attained a maximum thickness of at least one mile, or more probably one and a half miles, about 8,000 feet. The gradients of its surface were similar to the slowly ascending slopes by which the ice-sheets of Greenland and the Antarctic Continent rise to altitudes of about 2 miles above the sea. In the lower quarter or sixth part of the ice covering Manitoba—that is, to a height of probably 1,500 feet—much drift had been carried by its variable and partly rising currents.

Near the border of the ice-sheet during its time of accumulation, little drift could thus be carried into it, and therefore in the melting and recession of that outer part the englacial drift was generally inconspicuous; but at any considerable distance within the glaciated area, as a score of miles or more, the final melting set free much formerly englacial till and modified drift. Failure to recognize the origin of these deposits in New England has led a recent investigator of its glacial history to add, erroneously, as the present writer thinks, a late and distinct stage of glaciation to account for what seems to me an envelope or mantle of englacial drift spread over that region.[5]

The processes of drift transportation and deposition here emphasized were well stated by Prof. N. H. Winchell in 1873,[6] by Prof. C. H. Hitchcock in 1878,[7] and by me in 1876 and 1878 and in numerous later

[5] Frederick G. Clapp: Complexity of the Glacial Period in northeastern New England. Bull. Geol. Soc. Am., vol. 18, pp. 505-556, with plates 57-60, February 20, 1908.

[6] The drift deposits of the northwest. Popular Science Monthly, vol. III, pp. 202-210, 286-297 (especially page 294, relating to superglacial drift).

[7] Geology of New Hampshire, vol. III, pp. 282, 283, 309, 326, 333-338.

papers.[8] At the present day these processes are exemplified by the Malaspina Glacier or piedmont ice-sheet in Alaska, which during the last century has been much reduced in area and thickness; but the Greenland and Antarctic ice-sheets, which are now constant or increasing by snowfall, have no superglacial drift.

Conditions of the Origin of Eskers and Kames

In my first paper on this question, before cited, written 33 years ago and based on my studies in New Hampshire, the rivers forming eskers were thought to be mostly subglacial, although in many instances they were supposed to flow in "deep channels along lines of depression upon the surface of the glacier." The latter explanation, however, soon appeared to me preferable for all the eskers that then and subsequently I have examined, while quite short ridges and knolls or hills of the same gravel and sand, called kames, are ascribed to sudden and brief deposition by such ice-walled rivers close to their mouths.[9]

Believing that the ice-sheet nearly everywhere contained much englacial drift, I deem the absence or very rare occurrence of boulders in the gravel and sand of eskers and kames to be a conclusive argument against their subglacial deposition. Nowhere except on the western part of Birds Hill have I found or learned of an esker enveloped with till, as would apparently be common if these gravel ridges were formed beneath the border of the departing ice-sheet. Because only the west end and north

[8] Proceedings of the American Association for the Advancement of Science, vol. xxv, for 1876, p. 218; vol. xxviii, for 1878, pp. 299-310.

Geology of New Hampshire, vol. iii, 1878, pp. 9, 10, 175-176, 285-309.

Final Report of the Geological and Natural History Survey of Minnesota, vol. i, 1884, pp. 440, 603-604; vol. ii, 1888, pp. 252, 254-256, 409-417.

Bull. Geol. Soc. Am., vol. 3, 1892, pp. 134-148; vol. 4, 1893, pp. 191-204; vol. 5, 1894, pp. 71-86; vol. 6, 1895, pp. 343-352; vol. 7, 1896, pp. 17-30; vol. 8, 1897, pp. 183-196.

American Geologist, vol. x, 1892, pp. 339-362; vol. xii, 1893, pp. 36-43; vol. xiv, 1894, pp. 69-83; vol. xvi, 1895, pp. 100-113; vol. xix, 1897, pp. 411-417; vol. xx, 1897, pp. 383-387; vol. xxiii, 1899, pp. 369-374; vol. xxv, 1900, pp. 273-299.

Proceedings of the Boston Society of Natural History, vol. xxvi, 1893, pp. 2-17.

[9] Geology of New Hampshire, vol. iii, 1878, pp. 12-14, 43-48, 62, 71, 76, 84-93, 99, 106-108, 115, 117, 127, 137-138, 144, 147, 155, 162, 167-170, 174-176.

Final Report, Geological and Natural History Survey of Minnesota, vol. i, 1884, pp. 444, 582, 624; vol. ii, 1888, pp. 168, 185, 234, 486, 490, 550.

Proceedings of the American Association for the Advancement of Science, vol. xxviii, for 1879, pp. 303-304.

Proceedings of the Rochester, New York, Academy of Science, vol. ii, 1893, pp. 181-200.

Bull. Geol. Soc. Am., vol. 12, 1894, pp. 71-86.

American Geologist, vol. xiv, 1894, pp. 403-405.

U. S. Geological Survey Monograph xxv, The Glacial Lake Agassiz, 1895, pp. 157, 179, 182-188, 210.

slope of Birds Hill, for about a mile, are covered with till and boulders, while they are absent from the top and south slope, they seem impossible to be ascribed to an unmelted arch of the ice-margin inclosing the glacial river in a tunnel, but to be due to a slight readvance of the ice-front from the north side of the glacial river.

The conclusion that there was much englacial drift, which became exposed at last on the thinned ice-margin, carries with it the consequent reference of eskers and kames not to subglacial but to superglacial drainage. Melting of the ice-sheet near its receding boundary at the end of the Glacial period was probably far more rapid than is known anywhere on glaciers and ice-sheets of the present time; so that any crevasses or moulins would speedily be obstructed by drift carried into them, causing the rivers from the ice melting and rains to flow down on the surface of the ice to its margin.

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RELATIONSHIP OF NIAGARA RIVER TO THE GLACIAL PERIOD[1]

BY J. W. SPENCER

(*Read before the Society December 29, 1909*)

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PREFACE

In my investigations leading to "The Evolution of the Falls of Niagara" the most important problems were those bearing on the changing physics of the great cataract. To a relatively small extent the valleys buried beneath the drift produced effects, but that which was written on the features of the drift was only preliminary and should not be considered as a complete investigation of the subject, as lack of time did not permit of a full treatment. The river was regarded in a general way as post-glacial for that region only. With those notes now amplified by more complete details and the features still impressed on my mind, a better description can be given of the changing Pleistocene formations in this locality than that previously published.

STUDIES OF THE WHIRLPOOL-SAINT DAVIDS VALLEY

The peculiarities of the Whirlpool were first described by Lyell in 1841. He thought the Niagara River formerly passed by this now buried

[1] Manuscript received by the Secretary of the Geological Society January 15, 1910.

channel to the edge of the Niagara escarpment, 2½ miles northwest of the Whirlpool. During the next 40 years it seems this view was not questioned. However, in 1881, I showed there was a lower preglacial depression from Lake Erie than that over the rocks of Niagara Falls, and accordingly the Whirlpool-Saint Davids Valley could not have been the former outlet of the Erie basin, and that Niagara is a modern river throughout.[2] This was the revival of the study of the science of Niagara, but it is now known that there are at least three lower depressions across the belt of Niagara limestones than at the falls—all of which lie beneath the drift—and that the main buried outlet of the Erie basin is from 12 to 14 miles west of Niagara.[3] At one time I conjectured that the Whirlpool-Saint Davids Valley was preglacial. Then Dr. Julius Pohlman and Prof. E. W. Claypole[4] wrote on this buried valley. Later I modified my hypothesis and considered the buried channel as preglacial,[5] which view I have since maintained. However, as late as 1901, Dr. G. K. Gilbert thought that the gorge had been developed back to the Whirlpool during interglacial days.[6] Let us see what light is thrown on the subject.

Features of the Whirlpool-Saint Davids Gorge

The head of this buried canyon, for such it is, occurs at the south end of the Whirlpool, some 3 miles from the edge of the escarpment. Above this point is a smaller and shallower channel heading in the rocky divide 2 miles farther south. Beyond this ridge is another ancient valley, trending in the southward direction and deepening to 66 feet in a mile and a half, at the site of the falls themselves. In this distance the buried valley broadens from less than a quarter of a mile to over a mile, and gradually descends a more gentle gradient throughout a longer course than that of the Whirlpool-Saint Davids Gorge. This course is by way of the Falls-Chippawa and Erigan valleys, as described in "Evolution of the Falls of Niagara."

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[2] Proceedings of the American Philosophical Society, vol. xix, 1882, pp. 300-337 (read March 18, 1881). It was due to the inspiration of Prof. J. P. Lesley that all my subsequent investigations of the physical history of the Great Lakes, Niagara, and, indeed, of the submarine valleys, were made. He was the father of the science of topography and of its offspring, geomorphology.

[3] J. W. Spencer: Falls of Niagara; their evolution and varying relations to the Great Lakes; characteristics of the power and effects of its diversion. Geological Survey of Canada, 1907, pp. xxxi, 490, map, 46 plates, 30 figures.

[4] Pohlman: Proceedings of the American Association for the Advancement of Science, 1883-1887, and Transactions of the American Institute of Mining Engineers, 1889, and Claypole in Science, 1886, p. 236.

[5] American Naturalist, 1887, pp. 269-271.

[6] Gilbert: Map of Niagara River, 1901.

The buried gorge leading from the Whirlpool is bounded by compact limestones with their faces steep, except where these are rounded and glaciated, with striations along the direction of its course. In breadth the ancient and now buried gorge increases from 1,400 feet at the Whirlpool to 1,800 feet in a distance of 2½ miles. Having discovered in this gorge, at a depth of 186 feet, the remains of a buried interglacial forest, its glacial history is the theme of this paper.

As shown by Professor Coleman, the first announcement of the occurrence of interglacial beds in Canada was made by my friend, the late Mr. D. F. H. Wilkins. The locality was at Port Rowan, on the shores of Lake Erie.[7] This was in 1878. A little later the original work at Scarboro Heights, just east of Toronto, was published by Dr. George Jennings Hinde.[8] This was the foundation of interglacial geology in the Ontario basin. The locality has since been studied by many, especially by Prof. A. P. Coleman, Prof. D. P. Penhallow, Dr. William H. Dall, Mr. Simpson, and Mr. S. H. Scudder, who have examined the structure and the plants, shells, and insects. These drift deposits fill and are banked up over the trough of the preglacial outlet of Georgian Bay, discovered by the writer in 1888. The drift filling the Whirlpool-Saint Davids Valley can now be brought into comparison with the drift deposits on the northern side of the lake.

Pleistocene Deposits of Whirlpool-Saint Davids Gorge

In the neighborhood of the gorge the surface of the Niagara limestone floor has been planed off, polished, and grooved, the strongest striations being in the direction of south 60 degrees west, and weaker ones south 60 degrees east, and also south. These are best seen at the quarry on the mountain top east of Saint Davids, where the drift is reduced in places to only 4 feet. While the drift over the buried valley rises higher on the edge of the escarpment, its surface at the well to be described is 340 feet above Lake Ontario. The boring reached to a depth of 268.5 feet, or to 71.5 feet above the lake—that is, within 25 feet of the surface of the Whirlpool; but the buried channel may occur to 100 feet or more below the bottom of the well. After passing the upper 40 feet of clay, the materials could hold no water until reaching the level, 33 feet above the Whirlpool. The section obtained was as follows:

[7] Canadian Naturalist, vol. viii, 1878, pp. 82-86.
[8] Canadian Journal, Toronto, vol. xv, new series, 1878, pp. 388-413.

SECTION OF DRIFT IN THE WHIRLPOOL-SAINT DAVIDS CANYON

	To depth of—	Height of base above Lake Ontario.
	Feet.	Feet.
Surface of ground	0	340
I. Till.—Reddish clay with few pebbles and glaciated stones[9]	40	300
II. Interglacial.—Rounded gravel, 2 feet, over light brownish, fine, sandy loam, which is also calcareous, 38 feet	80	260
III. Till.—Small angular to rounded gravel, mostly quartzitic, in red clay matrix, 4 feet; loam with gravel as above, 10 feet; angular gravel with little clay binding, 26 feet	120	220
IV. Interglacial and glacial (?).—Bluish clayey sand with angular fragments. (Boring here was rapid, with admixture of recovered materials)	186	154
V. Interglacial land surface.—Six inches of fine white sandy soil deoxidized, with twigs and a well preserved trunk of northern white spruce. It rests on a grayish clayey sand, which when the calcareous and ferruginous matter are removed is similar to the deoxidized soil above. This also contains twigs of wood	220	120
VI. Till.—Angular and subangular gravel, mostly quartzitic, size of peas, with some earthy binding materials in variable layers. At 6 feet below the top was brown rusty sand (indicating an interglacial surface), strongly magnetic. At 15 feet the fragments were large. Subangular at base	243	97
VII. Interglacial (?).—Loamy sand with quartzitic pebbles, which at base are rounded	259	81
VIII. Interglacial.—Very fine siliceous flour, somewhat calcareous, but very rich in magnetic sand. Deposit held water, flowed upward in casing for 8 feet, like cement, and stopped the boring	68.5	71.5
IX. Interglacial (?) or glacial (?) to more than	293	47
(This is the level of the whirlpool, but the drift may continue for 50 or 100 feet less or more.)		

At well number 2, near by, the upper red clay passes into blue clay; and below is the loamy sand, which is well developed at well number 4 on my map. The upper layer holds water, but in the deep well no water was retained between the upper clay number I and series number VIII. At a locality 3 miles above the mouth of Niagara River, and extending below the level of Lake Ontario, occurs a blue clay in an ancient depression

[9] See Evolution of the Falls of Niagara, p. 133.

which has not been correlated with the deposits that were sheltered in the ancient canyon, but the topography in both shows eroded valleys, excavated out of the Medina shales of very much greater size than any later ones of interglacial or postglacial date.

Neighboring Drift Deposits

The surface clay rests on the polished rock northwest of the falls, and refills the now buried Falls-Chippawa Valley. Here beneath the surface clayey till the stratified sandy loams of number II are well shown in the sides of the bluffs.

Over the mouth of the buried Whirlpool-Saint Davids Channel and extending a short distance westward is the esker-like ridge of sand and gravel rising at one point to 442 feet above the lake. The gravel pits, opened to a depth of 50 feet, show cross-bedding, etcetera,[10] and these deposits have been penetrated to 100 feet or more without change of character.

The Erigan valley and canyon, which formed the ancient outlet of the Erie basin, from 12 to 14 miles west of Niagara Falls, was finally obstructed by an isolated ridge, in many places composed of stratified sandy clays and gravels, but with a till occurring at the summit which is nearly 650 feet above Lake Ontario, while stiff clays are found in the valleys descending to the northward. To the south of this ridge, beneath the covering of 8 feet of clay, the borings were carried to 132 feet, or to 80 feet below the level of Lake Erie, entirely through the quicksand which fills the now buried Erigan Valley. On the ridge Fonthill referred to is a fragment of the Forest beach, or the last shoreline of Lake Warren. Then the kamelike ridge of Lundys Lane, just west of Niagara Falls, is another interesting drift deposit; but these localities require more complete study.

Forest Glen and older Epochs

The key to the relationship of the Pleistocene deposits in the Niagara district was the discovery of the ancient spruce wood, which belongs to a climate cooler than that of the Niagara district of the present day (Penhallow), and to this is to be added the unusual occurrence of the bleached white quartz sand in which wood and twigs still occur. This is simply the soil deoxidized by the decaying vegetable matter. Beneath a depth of about 6 inches it rests on lower undeoxidized soil, also containing twigs with highly oxidized strata just below. These features show that the deep

[10] See work cited before, p. 127.

Whirlpool-Saint Davids Channel was open to a depth of 186 feet below the present surface and was covered by forest. All of the deposits here were brought from the north and were not carried from the Erie basin. Whether the channel was previously filled with drift can not now be known.

The deep trench corresponds to the great interglacial erosion valley found on the north side of Lake Ontario (see below). The spruce wood makes a paleontological connection with the upper Toronto beds. Whatever filling has been removed from the higher portion of the valley was carried away by the local drainage, which excavated it to a depth much lower than the rocky Lyell ridge north of the falls. Still the drift in the buried channel beneath the Forest Glen has been penetrated to a depth of over 100 feet, and it may be double this amount.

So far there are known to be at least two glacial formations older than the Forest Glen and two newer, with apparently a third layer of till before reaching the surface of the plateau, not to speak of the esker-like ridge at the mouth of the ancient gorge. These features place Niagara River near the close of the Pleistocene period, as it cuts through the most recent of the long succession of till formations found in this locality, although the glacial history was not completed in the Saint Lawrence Valley to the northeast.

Correlation of the Whirlpool Drift with that of Scarboro Heights

My investigations of the superficial formations of Ontario were primarily for the study of the deserted beaches, yet in many places there was found evidence of three layers of till, not to mention the morainic ridges. At Scarboro Heights, just east of Toronto, Dr. G. J. Hinde found fossiliferous beds passing below the level of Lake Ontario, in a pre-existing erosion trough, and a bed of till farther west, in Toronto, which he thought passed under the interglacial Scarboro beds. Carved out of them he found great erosion valleys. These were refilled or covered with overlying accumulations of till separated by interglacial beds.[11] Professor Coleman describes a fourth layer of till.[12] From a depth of 41 feet below lake level to 60 feet above, it has been found by the gentlemen before mentioned that the interglacial beds contain flora and fauna indicating a climate similar to that of the present day in a latitude several hundred

[11] But the older till is here as yet only known by the occurrence of the overlying and redeposited beds now forming interglacial series.

[12] See Professor Coleman's papers.

miles to the south of Niagara. Overlying these beds are others containing a flora belonging at present to a belt 200 miles to the north. These occur up to an elevation of 150 feet above Lake Ontario.[13] The fossiliferous beds of both series have been named the Toronto formation by Prof. T. C. Chamberlin. In correlating the fossiliferous beds with the Pleistocene series of the west, Prof. Frank Leverett provisionally thinks that they are newer than the Illinoisan till.

My original measurements of the height of the Iroquois beach just east of Scarboro Heights and those at the mouth of Niagara River show that the post-Iroquois warping amounts to 75 feet; so that, although the Forest Glen deposit occurs at 154 feet above the present lake level, with its correlative back of Toronto at 150 feet, there was an actual difference in height of 79 feet before the warping, but the land surface of the two localities probably varied.

The cool climate beds at Scarboro Heights were dissected by a deep glen, as first pointed out by Hinde, similar to that of the reopened Whirlpool-Saint Davids Valley, before the accumulation of the succeeding Pleistocene deposits, and the phases of erosion and climate are identical in the two localities. Indeed, the amount of erosion was very great. There has been found nothing of similar magnitude on the two sides of the lake. For this epoch of land erosion in the Ontario basin, which would seem to be post-Illinoisan, I apply the name of Forest Glen. This section substantially adds to our knowledge of the Glacial period in the Ontario Valley. The drift below the Forest Glen seems to fill a hiatus between the beds of colder and warmer climate at Toronto, while the warmer beds mentioned should only occur in the Niagara district below lake level, the recent tilting of the land causing the flooding of this region.

Whether the upper series of till above the Forest Glen and those at Toronto are merely alternations of the Iowan and earlier stages of the Wisconsin drift in this region or not, will be left to others to investigate, but the whole series shows that a very nearly complete succession of glacial deposits, except the late Wisconsin, was accumulated in the Niagara district before the birth of the river, which cuts through the most recent till of the region.

Summary

In the borings made in the Whirlpool-Saint Davids Channel, there have been discovered the remains of a cool climate forest and soil at a depth of 186 feet below the surface, with the proof of three or four glacial formations since that time, like the Pleistocene series at Toronto. Before that

[13] Loc. cit.

cool epoch of the Forest Glen, which may be considered a post-Illinoisan, at least two glacial formations have been left in the buried channel, which below is further filled by 100, or perhaps nearer 200, feet of drift, some of the deposits of which may represent a still older Glacial epoch. There seems no reasonable doubt that the ravine at Forest Glen had the same date as the ravines in the fossiliferous beds east of Toronto. The origin of the Whirlpool Gorge is thus shown to be older, by at least two stages, than the fossiliferous beds mentioned (which are supposed by Chamberlin and Leverett to be an equivalent of the post-Illinoisan interglacial period), with still an underlying accumulation of 100 to 200 feet undetermined by direct observation. This lowest drift lies in a rock-bordered valley which has suffered an amount of erosion enormously greater than that during or since the Glacial period. From all the evidence found I can therefore only conclude that this new filled trough is of preglacial origin. The age of the modern Niagara River is also found to be younger than the glacial deposits about the western end of Lake Ontario, though not so recent as the later Wisconsin accumulations in other localities.

Having described the relationship of Niagara River to the older drift deposits, its relationship to the latest ice-sheet should be referred to. Before the birth of the falls, the ice had receded beyond the greatest of all the moraines of Ontario, which lie between Lake Ontario and Lake Simcoe and between this lake and Georgian Bay, a distance of more than 120 miles north of Niagara Falls; so that the drainage of Lake Huron then passed down the Trent Valley, as discovered by the instrumental measurements of the writer in 1888, since confirmed by Gilbert and Taylor, and later remeasured by Goldthwait. From the terrace north of Lake Nipissing, identified by Taylor as belonging to the level of the Algonquin beach, the ice-sheet had receded 230 miles or more to the north of Niagara before the birth of the falls. But the Ottawa Valley farther down was still blocked. The Ontario Valley was also open to at least near the eastern end of the lake, so that it permitted the flow from Algonquin Lake down the Trent Valley, although the ice was not removed from the Saint Lawrence Valley till some time after the birth of the falls. This was the last ice-sheet, concerning which at present we only know that it disappeared so long ago that there was time for the excavation of the inner gorge of Niagara River, extending from Lake Ontario to a point inside the canyon of Niagara, since reflooded and drowned to 180 feet by the subsequent northeastward tilting of the region.

NOTE.—Erigan is the name given to the buried valley and canyon which formed the preglacial outlet of the Erie Valley.

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RELATIVE WORK OF THE TWO FALLS OF NIAGARA

BY J. W. SPENCER

(*Read before the Society December 29, 1909*)

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PREFACE

The special interest in the Falls of Niagara, apart from the scenic and economic, lies in two scientific directions. One of these is connected with the researches into the remarkable physical changes, not only of the direction of the drainage of the upper lakes, but of the whole lake history and the production of the falls themselves. Although these questions are primarily American, the opportunity is better afforded here than elsewhere of studying the physico-geological problems involved, and hence the falls are of general concern. The other interest is that connected with the age of the falls, as they furnish the best measurements of the amount of geological work that has been performed in a given time, thus becoming a chronometer which, when brought into comparison with the work effected in other localities, will enable us to have definite ideas of glacial time. In this respect the subject is of world-wide interest. Any reasonable variation suggested can only lead to more precise results. To two minor omissions in my previous treatment of the past recession of the Falls of Niagara[1] Dr. G. K. Gilbert has called attention, namely, the work of the American cataract and the variation in the relative effective work of the two falls. These questions I have since partly considered.[2]

RATE OF RECESSION OF THE AMERICAN FALLS

For want of sufficient time and opportunity and on account of my impression of the relative unimportance of the smaller cataract, I gave but

[1] J. W. Spencer: The Falls of Niagara; their evolution and varying relations to the Great Lakes; characteristics of the power and effects of its diversion. Geological Survey of Canada, 1907, pp. xxxi, 490, with maps and illustrations.
[2] Science, vol. xxviii, 1908, pp. 754-759.

little attention to this topic, which under other conditions would have deserved more prominence. Between the time of the survey by Prof. James Hall, in 1842, and that by Mr. Aug. S. Kibbe, in 1890, there had been only a small recession, and since then apparently so little change had occurred that I did not make a resurvey of them in 1905. My impressions were correct, for by other surveys of 1905[3] and 1906[4] it has been found that scarcely any appreciable amount of rock has fallen. The measurements showed a recession from 1842 to 1890 of 0.60 foot a year, but the average amount from 1842 to 1906 is now found to be 0.45 foot. Originally I stated that since 600 years ago (now corrected to 550 years) "the American Falls do not seem to have retreated more than 110 feet, if so much, in excess of the unknown widening of the gorge from frost action" (page 38). This would represent, if correct, only 0.20 foot a year. This might have left a wide correction for the determination by future generations, but now it can never be done, as the power diversion has already rendered it impossible. Let us put on record how the recession of the smaller falls really compares with that of the main cataract.

While the American cataract suffered a mean recession of only 29 feet between 1842 and 1906 (by actual measurement), the main, or Canadian, Falls retreated 265 feet for a mean breadth of 1,200 feet. Fragments of the original banks are still preserved. As the gross errors of observation are equal in the two cases, these are reduced to a relatively small amount in the latter instance, even though the undercutting before 1842 had considerably progressed. The undercutting in the case of the fallen Table Rock reached from 40 to 50 feet, and nearly the same amount is still to be seen overhanging in front of Wintergreen Flats, some miles down the gorge.

Under these conditions, especially as the superior ledges of hard rocks at the American Falls now project but little, and as there are huge masses of rocks fallen at their foot, it would seem that the undercutting had progressed far when Professor Hall made his survey. This undercutting has caused an excessive amount of collapse of the upper layers of rock since his time, especially as it does not appear how the falls could have receded more than 200 feet since the separation of the two cataracts. All these considerations show that absolute measurements of the recession of the American Falls are not obtainable for calculating the age of the gorge; yet, on the other hand, close estimates of their rate of retreat can be made.

As the diameter of the main falls is 1,200 feet and of the smaller one

[3] By Mr. Basil Hall for the U. S. Geological Survey.
[4] U. S. Lake Survey.

920 feet, exclusive of islands, the rate of 0.45 foot observed since 1842 should be reduced to 0.35 foot if it be compared with the work of the main cataract. At the time of my investigations, engineers generally conceded to the smaller falls 20 per cent of all the water. In opposition, I reduced this to 6 or 7 per cent. It has since been found by the U. S. Lake Survey to be scarcely 5 per cent; so that my results show only a practically negligible error. With a proportional efficiency in recession (as the mean rate at the Canadian Falls is 4.2 feet a year), this would give a theoretical rate of 0.21 foot for the smaller falls; but as this amount of water is acting on only 920 feet of rock face in place of 1,200 feet, for comparative purposes the rate should be raised to 0.27 foot a year, or somewhat greater than was assumed by me (0.20 foot) in "Evolution of the Falls of Niagara."

Again, those calculations are within limits of error, for the falls have decreased their height by 50 or 60 feet since the separation of the two cataracts,[5] which has favored the accumulation of talus at the foot of the American Falls; but Peter Kalm, the naturalist, most positively asserts that their height was 137 feet[6] (French measure), which equals 145 English feet. The reduction in the height of the falls was due to the falling of the gorge walls into the channel at Whirlpool Rapids. Kalm's statement being accepted as correct, it would seem that the Whirlpool Rapids have reduced their height by 22 feet since the year 1750. The lately reduced height of the falls, as mentioned, was finally established from the soundings under the Canadian Falls.

On page 22, in his bulletin on the recession of the falls,[7] Doctor Gilbert suggests that the rate of recession of the American Falls may be 0.32 foot a year, which is near that deduced by me (0.27 foot) as the mean since the separation of the two cataracts. However, these figures are not of value in investigating the age of the falls, as they are not derived from direct measurement, but they are of importance in showing that there is no apparent discrepancy between the relative work of the two falls, and also that any omission of this question did not derogate from the general conclusions as to the age of the Falls of Niagara based on work of the main cataract.

Relative Efficiency of the two Falls of Niagara

This is the other problem omitted from my monograph. In the two cases the rock formations are nearly identical, but the immediate results are very different. The main cataract, falling 158 feet to the cauldron

[5] Op. cit., p. 367.
[6] Op. cit., p. 435.
[7] Bulletin of the U. S. Geological Survey, no. 306, 1907.

below, passes the top of the resistant Clinton limestone (20 to 22 feet thick) at 12 feet above the surface of the basin below the falls, and reaches the blocks of the underlying talus at 72 feet below the surface, as found by my soundings; but the soundings farther away and other features indicate the depth of the river near the falls (where not covered by blocks) to be about 100 feet, although, farther down, the river is deeper, as explained in "Evolution of the Falls" (page 56). Toward the middle of the falls there is no shelf of Clinton limestone, although there is a projecting ledge supporting a talus and extending outward for nearly 1,000 feet from the original edge of the falls on the Canadian side. Here have been two stages in the recession of the rock wall, or an undercutting beneath each of the two series of overhanging limestones.

The conditions at the American Falls are different. They are 167.5 feet high, and the hard Clinton limestones rise to 40 feet above the river at the northern end of the cataract, with the underlying shales also appearing above the river beneath the talus heap of fallen limestones, which also in places rise to more than 40 feet above the lower river; but the fallen mass must be much less than that beneath the water at the foot of the main falls. Thus it would seem that a precise measurement of the relative efficiency in erosion by the two falls is impossible. Add to the difficulty the fact that the falls have changed their height by a reduction from 220 feet to 167 feet, owing to the recently falling rocks at the Whirlpool Rapids forming a dam and raising the surface of the pool below the falls, within the last 300 years, though more than 160 years ago.[8]

Before the time of the rising of the waters in the basin below the falls there was a wall of shales and perishable sandstone layers (70 feet or more in height) beneath the hard Clinton limestones under the American Falls, so that the conditions of recession were much more favorable then than now; but after the rising of the river these lower beds were protected, and with the subsequent collapse of the overhanging walls the accumulated talus became further protective. The talus is now being slowly removed, owing to the direct impact of the falling water, aided by frost action. The observations on the deserted floor of the river at Fosters Flats left the conclusion that the fallen blocks of limestone have been largely carried away by solution.[9] The talus heap under the American Falls (due in part to the undermining by the former higher cataract) is now being worn away with the maximum efficiency, checked only by occasional gales of wind.

[8] Peter Kalm, writing in 1750, said: "This fall, by all the accounts that have been given of it, has grown less and less, and those who have measured it with mathematical instruments find the perpendicular fall of water to be exactly 137 feet" (French).

[9] Op. cit., pp. 174 and 177.

In contrast, the greater falls impinge on the drowned talus only after they have passed through a stratum of 72 feet of water, forming a very thick cushion, thus diminishing the mechanical effect of the falling water. An effective descent of both falls (allowing for the acquired velocity at their crests) may be taken at 180 feet. Even without knowing the soundings, it would seem improbable that the falls could excavate in the hard shales to 192 feet, as found farther down the gorge, or to a depth beneath the surface of the river greater than the height of the falls. This was rendered still further unlikely by the fact that in the deep channel the hard Medina sandstones had also been penetrated, while now the soundings show that the present descent of the falling water does not penetrate them.[10] Thus while the full efficiency of the American Falls is at work on the exposed rocks and talus masses, a third, or perhaps more, of the effective force of the great mass of water of the Canadian Falls is lost in friction, heat, and the counterbalancing hydrostatic pressure of the river.

While there is still some current when the falls reach the talus at a depth of 72 feet, yet it is broken up on the talus, just as is seen above the river surface below the American Falls, and it soon loses its greater mechanical effect among the fallen blocks; but the chemical solution by the circulating currents, which can no longer shift the blocks, is most active; else the talus heap would grow so as to produce rapids in place of falls. Such results may be seen at some small cataracts.

Some unfinished experiments of falling water in which I had the opportunity of taking part led me to conclude that when the descent is like that of a rapid, a gentle current may reach to a considerable depth, slowly moving fine particles, as in the deeper holes of a stream where alluvium is being deposited; but when the descent is by a considerable fall into a basin, the blow is so checked that the current capable of moving fine sand reaches approximately to only two-thirds of the descent of the fall above the surface of the basin. The experiments were made on already loose materials, and it seems to me that the relative result would be further reduced where the force of abrasion is applied to solid rocks.

Observations and measurements made in determining the efficiency of a water power where the water descends 208 feet in a penstock of 3 feet diameter, having an inclined position, gave the gross amount of work as 1,631 horsepower, while the relative efficiency when using the full volume of water was 78.5 per cent; but when using only from 90 to 67 per cent of the water it actually rose to 80 per cent, thus showing greater power where there was some freedom in the tube. Using 50 per cent of the water, the efficiency fell only to 76 per cent, or 2½ below that of the greatest power. The use of 40 per cent yielded 70; 30 per cent brought

[10] Op. cit., pp. 56-58.

the efficiency down to 60, below which the loss through friction in the inclined pipe and turbine was relatively still greater. But this mechanical contrivance, using only about 70 cubic feet per second in a relatively small pipe, can not be compared with the free flow of 10,000 cubic feet per second, as in the case of the American Falls, where there is neither tube friction nor turbine losses.

The reason for comparing the relative work accomplished by the two falls lies in the fact that throughout the greater life of Niagara the discharge was more nearly like that of the American than of the Canadian Falls. At that time the volume was three times as great as the present American Falls, but the mean height of the uppermost cataract on which the determinations were made was only seven-twelfths that of the effective height of the American Falls; so that the work performed was less than double that of the present smaller cataract. There is no suggestion of any retardation in the lower river, but the lake level probably held back the river so that there would be a pool at the foot of the falls of a few feet in depth, as is commonly seen elsewhere; but the pool was above the surface of the Medina sandstone and perhaps its depth may not have exceeded 10 feet. At one time the river was well drained when the lake was much lower than now, although later it backed up and drowned the deeper channel described in "Evolution of the Falls of Niagara." The basin below the main cataract now forms a safety balance, as it were, being excavated to a depth according to the mechanical force of the falls,[11] and it appears to me that a similar balance has always maintained, else with the direct action on the bottom rocks, like at the American Falls, the relative efficiency in erosion would be greater than that of the Canadian Falls descending into its deep basin, thereby losing much of its power. The frost action at the smaller falls, as pointed out by Prof. James Hall, is greater than under a great sheet of water.

Whether the work performed by the changing conditions of the Falls of Niagara be within 10 per cent of that computed or require a correction of double this amount or more, the investigations give us an approximate result, based on direct measurements and not on mere opinions or hypotheses. There now seem to be no important omissions in the determination of the changing work of the falls. It was well to raise the questions here discussed, and this paper is offered as an additional chapter to the monograph on the Falls of Niagara, and the analysis of the features here considered strengthens the conclusions previously reached. They show that there is a balance maintained in the relative depth of the pool beneath the retreating cataract.

[11] The variable depth of the river corresponds to the loss of erosion, as shown in the work cited, pp. 344, 350, 351.

AMERICAN FALLS

1,000 feet long, frozen and drained February 17, 1909 (Spencer)

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INTERRUPTION IN THE FLOW OF THE FALLS OF NIAGARA IN FEBRUARY, 1909

BY J. W. SPENCER

(*Read before the Society December 29, 1909*)

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PREVIOUS FLUCTUATIONS

Since the year 1890, the mean level of Lake Erie has fallen about 1 foot[1] and the basin above Goat Island about a foot and a half. From that year until the end of 1905, the mean annual fluctuations varied scarcely more than 1 foot, while in one case the mean monthly variation reached nearly 2 feet; but during the progress of storms, when the wind has changed to the opposite direction, the fluctuations have been found to reach 5 or even 6 feet.

FLUCTUATIONS OF 1909

During January and the early part of February, 1909, the lake level was below that of the mean, but on February 10 Lake Erie rose nearly 3 feet above the mean annual average height (1889-1905, inclusive), while in the following and succeeding days it fell with a northerly wind to 4 feet below the mean (as shown by the records of the gauges as furnished the U. S. Lake Survey). This was on February 14. At this time the weather was very cold. On account of the reduced depth of the water on the upper rapids, as the ice was forming, it remained anchored to the projecting rocks and was not carried over the falls; so that the New York channel and the main channel to about 600 feet outside of Goat Island were frozen over, except one small lead, which scarcely showed any current where ordinarily it is a rushing torrent. It must be emphasized that the ice was not an accumulation of blocks carried down from Lake Erie, as often occurs, like in the jam of the following April. As the blizzard con-

[1] J. W. Spencer: Evolution of the Falls of Niagara. Geological Survey of Canada, p. 190.

AMERICAN FALLS
1,000 feet long, frozen and drained February 17, 1909 (Spencer)

tinued, with its falling snow, the lake level fell to the lowest on February 14, and almost all of the water beneath the ice was withdrawn, so that the American Falls of 1,000 feet in breadth were drained, except four or five insignificant streamlets, as shown in plate 32. The eastern side of the main falls, adjacent to Goat Island, was drained for 800 feet, as may be seen in plate 33, figure 1. The end of the ice-covered rock rim of the first cascade of the upper rapids, with the frozen river in front of Goat Island, is shown in plate 34, figure 1. On the Canadian side, the main falls, which have already been curtailed by 415 feet, due to power diversion, was further drained by about 200 feet, as illustrated in plate 33, figure 2. Another photograph, not reproduced, shows that in the middle of the main cataract the rocks almost reached the surface; but without allowing for these thinly covered masses, the total shrinkage of the main falls amounted to a reduction of the crest line from 2,950 feet (in 1901) to 1,600, and the diameter was shortened from 1,200 feet to less than 800.

From the foregoing it may be understood that the cause of Niagara "running dry," as expressed by the newspapers, was due to the recent lowering of the river level (partly owing to power diversion), thus permitting the formation of the ice-barriers, which cut off the reduced supply of water during a strong northerly wind, in very cold weather, at a time of the low stages of Lake Erie. This condition continued for nearly a week. Had there been no ice, the extreme effect of the wind would have lasted for only a day, even if the volume of water had been below the normal amount. The Whirlpool Rapids were lowered by many feet, so that the usual rushing, boiling, pitching, torrents seemed tamed, as may be seen in plate 34, figure 2.

Similar Occurrences

Within the historic record the only other times when similar phenomena have been seen were the following: On March 29, 1848, the ice from Lake Erie blocked the river for one day, as described by the Hon. Peter A. Porter; on March 22, 1893, a partial stoppage occurred, which also appeared to have been due to the blockade of lake ice; and on February 29, 1896, there was another shrinkage of the falls. None of these cases were comparable to that of 1909, when the phenomena lasted for nearly a week from February 14. With the continued draining of the falls, a repetition of these features should be expected. In part, they represent what will become a permanent condition, owing to power diversion. The above is from my personal observations, and the photographs are of my taking or those of Mr. E. Deming Smith, of Niagara Falls, who accompanied me.

Note.—In March, 1910, owing to the shoaling of the waters on the upper rapids, the ice was caught and so barricaded the New York channel that the American Falls were again damaged, being broken into four parts.

FIGURE 1.—GOAT ISLAND END OF MAIN OR CANADIAN FALLS
Drained February 16, 1909 (Spencer)

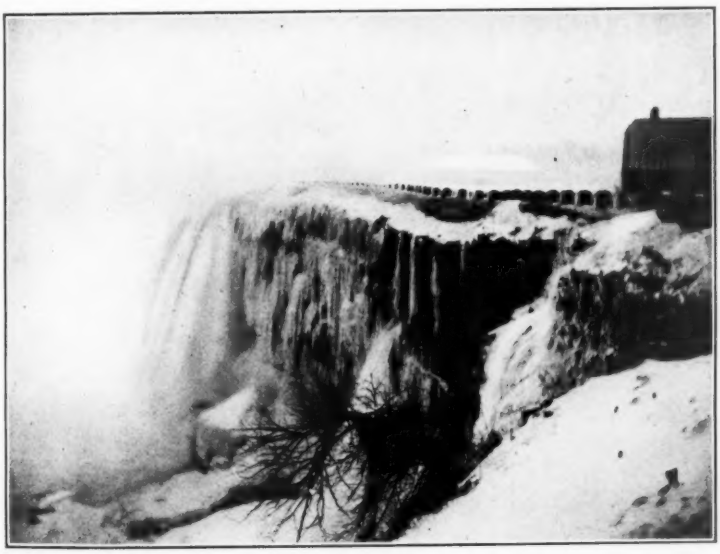

FIGURE 2.—WESTERN END OF MAIN FALLS
Already curtailed by length of wall. Further drained February 16, 1909 (Spencer)

FIGURE 1.—END OF ICE-COVERED AND DRAINED RIM OF FIRST CASCADE OF UPPER RAPIDS, ABOVE THE "SISTER ISLANDS," FEBRUARY 17, 1909 (SMITH)

FIGURE 2.—WHIRLPOOL RAPIDS, AT VERY LOW WATER, FEBRUARY 17, 1909 (LOOKING DOWNWARD) (SMITH)

FIGURE 1.—NEWLY CLEARED FIELD COVERED WITH MOUNDS OF ANTS NEAR RIO UTINGA, STATE OF BAHIA, BRAZIL

The largest of these mounds have bases of six or seven meters. Photograph by R. Crandall, 1907

FIGURE 2.—MOUNDS OF TERMITES IN AN OLD FIELD NEAR QUELUZ, STATE OF MINAS GERAES, BRAZIL

White spots in the background are the mounds. Photograph by Dr. Gonzaga de Campos, 1909

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GEOLOGIC WORK OF ANTS IN TROPICAL AMERICA[1]

BY J. C. BRANNER

(Read before the Cordilleran Section of the Society March 25, 1910)

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[1] Manuscript received by the Secretary of the Society April 29, 1910.

Introductory

In 1900 I published a short paper on the geologic work of ants in the tropics.[2] Since then a good many additional observations, notes, and photographs have been made, and the most important of them are here brought together in a single article.

There are many brief notes on the work of ants scattered through the writings of travelers in tropical countries, but these notes are for the most part repetitions of rather vague and sensational stories which make no claim to accuracy of statement, so that they would add little or nothing to the value of the article. No attempt has, therefore, been made to use such notes except in so far as they seem to afford new or important corroborative evidence. At the same time it is realized that some of the things that ants do in tropical countries are so remarkable that those who have no personal experience of them may be pardoned for regarding the stories told about them with a certain amount of suspicion. For this reason I have quoted directly, and sometimes at considerable length, from some of our most trustworthy scientific writers, especially from Bates, Belt, and Spruce, all of whom are naturalists to be taken seriously.

The best any one can do who has not seen the work of ants in tropical countries is to turn to what can be seen in temperate regions. But it should be insisted on that the work done by ants in temperate zones is, with a few exceptions, of no geologic importance at all as compared with that done by them in some parts of the tropics.

The work of the ants, in so far as it is of geologic importance, consists chiefly of their nests, habitations, refuse heaps, or mounds, above ground and their burrows, tunnels, passageways, and other excavations beneath the surface, and the opening up of the soil and the subjacent rocks to the various atmospheric influences.

In the United States we have very little evidence of ants making either underground passageways or mounds of sufficient size or extent to have attracted much attention. Indeed, it seems to be generally conceded by entomologists that the ants of the northern part of North America are not as enterprising as those farther south, or even as those of Europe. Forel seems to have found the structures of our North American ants so insignificant that he avoided speaking of them as having mounds at all. Certainly the little ant-hills we have seen in most parts of the United States are too insignificant to attract the attention of geologists. In the South and Southwest they are somewhat more conspicuous, and in the semi-arid portions of western Texas and in Arizona, New Mexico, and parts of California they have attracted not a little attention.

[2] Journal of Geology, vol. viii, pp. 151-153. Chicago, 1900.

The western halves of Oklahoma, Kansas, and Nebraska and the eastern portion of Colorado are inhabited by mound-building prairie ants that are sufficiently abundant and sufficiently pugnacious to have attracted the attention of farmers and entomologists, if not of geologists.[3]

In the Western States generally ants are more abundant than they are in the East, but a writer on the ant-hills of southwestern Wisconsin says that in that part of the country he knows of at least a hundred so-called ant-hills within a radius of 5 miles, and he appears to regard this number as quite striking. Their mounds, he says, are as much as 75 centimeters in diameter and 40 centimeters in height.[4] These cases are mentioned simply for the purpose of contrasting the size and number of ant-hills in a region that seems to be regarded as pretty thickly inhabited with some of the typical localities in the tropical portions of South America.

Furthermore, in the tropical parts of America ants are not the simple and easily ignored insects with which we are acquainted in the temperate zones of the earth. Save in the cities, they are almost omnipresent. To the housekeeper they are not only never-sleeping pests, but they are bold and defiant robbers or sneak thieves, as circumstances require, and they can not be ignored. To the planters they are veritable plagues—they destroy the growing crops as completely as if they had been burned over. They do not wipe out a field of grain in a few hours as completely as do the locust swarms of Argentina, and then disappear, but they stay with their work right alongside of the crops, and with time they destroy them no less certainly. Unlike the locusts, they do not come and depart, but they stay right in one circumscribed area all their lives. *Farinha de mandioca,* the meal prepared from the cassava plant, or grain of a size small enough for them to carry, require to be guarded with constant care. I have known bagfuls of farinha de mandioca to be carried away by them. In short, the inhabitants have to be constantly on their guard against the ants, both indoors and out of doors, to say nothing of the mere inconvenience of their presence. Nor can their importance be regarded as whimsical in any sense; indeed, I am convinced that they are social, and even national, factors that are not to be ignored.

Nothing in the way of a biologic or systematic study of tropical ants is attempted in the present paper. However valuable such a study might be, it is the number of individuals, rather than the number of species, that concerns the geologist, though it is recognized, of course, that some

[3] T. J. Headlee and George A. Dean: The mound-building prairie ant (*Pogonomyrmex occidentalis* Cresson). Bull. 154, Kansas Agricultural Experimental Station. Manhattan, 1908.

[4] Hermann Muckermann: Psyche, vol. ix, pp. 355-360. Boston, 1902.

species are much more active agents than others. We need concern ourselves with only two large orders: the true ants belonging to the *Hymenoptera*, and the termites, or so-called white ants, neuropteroid insects which belong to the *Isoptera*, and are known all over Brazil by the popular Indian name of "cupim." And nothing is attempted in the way of a study of the architecture of their nests and underground passages, save in so far as such details will give a better idea of the geologic bearing of these matters.

The monumental work of Dr. Auguste Forel, "Les Fourmis de la Suisse," published at Zurich in 1874, will naturally be consulted by any one especially interested in ants themselves and in their habits and structures.

It may be useful to suggest in this connection, however, that though the ants of Switzerland and of temperate regions generally exhibit the same ingenuity and intelligence as those of tropical countries, as geologic agents they are very tame indeed in comparison with those of the tropics.

In studying the work of ants in the tropics one is constantly reminded of Mr. Darwin's studies of the work of earthworms. Mr. Darwin was able to give the quantitative results of his studies. In the case of the ants, unfortunately, quantitative results have not been possible. The time occupied by them in doing a given amount of work varies so much that quantitative observations, in order to have any value, would have to be carried on upon many colonies and for a long period of time. The results given at page 469 are an attempt at quantitative determination, but it will be observed that it is not known how many individuals took part in the work, while the time element involved in the calculation is entirely lacking. It is hoped that observations may be undertaken by geologists living in tropical countries with a view to settling these interesting points.

To illustrate this article especial pains have been taken to get as many photographs and sketches as possible of the above-ground structures of ants and termites, and the accompanying illustrations have been carefully made by Mrs. Starks from photographs, most of them taken in Brazil by myself or by my former assistant, Mr. Roderic Crandall, now geologist of the Geological Survey of Brazil (Serviço Geologico do Brazil). It seemed better to have the drawings made rather than to use the original photographs, in spite of the evident suspicion of exaggeration or alteration, whether intentional or accidental, to which all drawings are open. This redrawing was the more necessary because the photographs were taken hastily and under many unfavorable circumstances, and they are therefore often not good, or they are not available for reproduction as photo-

graphs, besides being of various inconvenient sizes. The illustrations are given because it is felt that they are the most impressive and most trustworthy witnesses one can put in evidence regarding the subject.

The true Ants

Abundance

Although ants are not everywhere equally abundant in tropical South America, their numbers are so large on an average as to promptly attract the attention of travelers, even when they do not excite their wonder. Residents, who might be expected to have conservative views on the subject, often speak of them as the owners of the land. Such a remark is at first regarded as merely facetious, but the character of some of the writers who make it entitles it to serious consideration. As long ago as 1648 Piso said that the Portuguese not inappropriately called the ant the "king of Brazil."[5]

One naturalist who spent some time in the country says, "Brazil is one great ants' nest."[6]

Belt says, "They are one of the greatest scourges of tropical America."[7]

A Brazilian traveler, speaking of the region of the upper Rio, Paraguay, says, "The ant and the different kinds of termites own the land."[8]

Another puts it in this fashion: ". . . ants . . . deserve to be considered the actual owners of the Amazon Valley far more than the red or the white man."[9]

Another writer says of them: "One seriously asks whether they are not the real conquerors of Brazil."[10]

These characterizations are all so sweeping that, taken alone, they are open to the suspicion of being merely picturesque and extravagant ebullitions rather than serious and truthful statements of fact. If they are based on some knowledge of the ants, these expressions seem to spring from more or less personal animosity toward those insects. And yet this very animosity, if it really exists, must come from a pretty uniform per-

[5] Formicæ autem hæ (*Rey do Brasil* Lusitanis non immerito dictæ, quod perpetuam tyrannidem exerceant) aliquæ Europæarum plane similes, aliquæ triplo majores & alatæ, omnivoræ sunt.

De Aeribus, Aquis, & Locis. Gvilielmi Pisonis Historiæ Naturalis & Medicæ, p. 9. Amsterdam, 1658.

[6] Rev. H. Clark: Letters home from Spain, etc., pp. 131, 173. London, 1867.

[7] Thomas Belt: The naturalist in Nicaragua, p. 79. London, 1874.

[8] Dr. Joao Severiano da Fonseca. Viagem ao redor do Brazil, vol. I, p. 352. Rio de Janeiro, 1880.

[9] Richard Spruce: Notes of a botanist on the Amazon and Andes, vol. II, p. 366. London, 1908.

[10] Adolph d'Assier: Revue des Deux Mondes, vol. xlix, p. 582. Paris, 1864.

sonal experience of them. It therefore seems best to quote directly a few more detailed statements regarding the abundance and habits of ants in Brazil. Certainly no one will be taken more seriously than Dr. Auguste Forel, who says that "the ant fauna of South America is perhaps the richest in the world from the systematic point of view."[11] In the paper cited 440 species of true ants are noted as inhabiting Brazil, out of a total of 2,000 known in the world.

But though it is with the number of individuals rather than the number of species that we are concerned, it is worth remembering that in many considerable regions a single species may occupy about all the ground space that it is possible for ants to occupy. A single species may thus fairly swarm and do a vast deal more work than several different species.

The true ants, evidently of a large number of species, are so abundant and are such serious pests in some places that the land is practically preempted by them. Travelers passing the night in the open have to be constantly on their guard against colonies of ants. Fighting such colonies under the circumstances is simply out of the question. When one finds himself in disagreeable proximity to them, the only thing to be done is to move at once and leave the ants masters of the situation.

Bates, speaking of a certain species, says (page 354):

"These Ecitons are seen in the pathways of the forest at all places on the banks of the Amazons, traveling in dense columns of countless thousands."

On the Rio Tapajos, in the Amazon Valley, Bates noted the

"quantity of drowned winged ants along the beach; they were all of one species, the terrible *formiga de fogo* (*Myrmica sævissima*), the dead or half-dead bodies of which were heaped up in a line an inch or two in height and breadth, the line continuing without interruption for miles at the edge of the water. The countless thousands had been doubtless cast into the river while flying during a sudden squall the night before, and afterwards cast ashore by the waves."[12] . . . "I was told that this wholesale destruction of ant-life takes place annually, and that the same compact heap of dead bodies which I saw only in part extends along the banks of the river for 12 or 15 miles" (op. cit., p. 206).

I have seen similar accumulations of dead female ants on the lower São Francisco and the Rio Paraguay, near Corumba, and at two places on the shores of estuaries near Aracaju, in the State of Sergipe.

Bates says the *formiga de fogo*, or fire ant, was so abundant at one

[11] A. Forel: A fauna das formigas do Brazil. Bol. do Museu Paraense, vol. 1, p. 89. Pará, 1895.

[12] H. W. Bates: The naturalist on the River Amazons, 4th ed., p. 201. London, 1875.

place on the Tapajos that there was scarcely a square inch of ground free from them. (Op. cit., p. 202.)

The only figures I am able to give in regard to the sizes of ant colonies are the estimates given by Azevedo Sampaio, a Brazilian entomologist who has studied the *saúbas*. He estimates the colonies at from 175,000 to 600,000 individuals.[13]

DESTRUCTIVENESS

In speaking in general terms of the destructiveness of ants in tropical America, Humboldt says:[14]

"Those who do not know the immense quantity of ants that infest every country within the torrid zone, can scarcely form an idea of the destruction and of the sinking of the ground occasioned by these insects. They abound to such a degree on the spot where Valencia is placed that their excavations resemble subterranean canals, which are filled with water in the time of the rains and becomes very dangerous to the builders. Here recourse has not been had to the extraordinary means employed at the beginning of the sixteenth century in the island of St. Domingo, when troops of ants ravaged the fine plains of La Vega and the rich possessions of the order of St. Francis. The monks, after having in vain burnt the larvæ of the ants, and had recourse to fumigations, advised the inhabitants to choose by lot a saint, who would serve as an *abagado contra las hormigas*. The honour of the choice fell on St. Saturnin, and the ants disappeared as soon as the first festival of this saint was celebrated. Incredulity has made great progress since the time of the conquest, and it was on the back of the Cordilleras only that I found a small chapel, destined, according to its inscription, for prayers to be addressed to Heaven for the destruction of the *termites*."

The destruction wrought by the true ants is confined chiefly, but not entirely, to agricultural products. It is no uncommon thing to find spots where certain ants are so abundant and so destructive that the planters simply leave them alone. Sometimes it happens that after clearing a piece of land, and beginning their planting, the farmers find the ants so destructive that those particular fields are abandoned. In the coffee regions certain ants, popularly known as the *saúbas*, are so destructive that a systematic and unceasing war has to be waged upon them in order to save the coffee trees. But their attacks are not confined to coffee trees by any manner of means.

The following description of the *saúbas* is given by Gabriel Soares de Souza, one of the earliest writers on Brazil (1587).[15]

---

[13] Azevedo Sampaio: Sauva ou Manhu-uára, pp. 50, 54. S. Paulo, 1894.

[14] Alexander de Humboldt and Aimé Bonpland: Personal narrative of travels to the equatorial regions of the new continent, vol. iv, p. 191. London, 1819.

[15] Gabriel Soares de Souza: Tratado descriptivo do Brazil em 1587. Revista do Instituto Historico do Brazil, vol. xv, p. 271. Rio de Janeiro, 1851.

What is said of that period is equally true today:

". . . Wherever they go they destroy the fields of mandioca, the orchards, orange trees, pomegranates, and vines. If it were not for these ants there would be many Portuguese vines and grapes in Bahia. These ants come a long way at night to find a mandioca field, and where they march they wear a path as if people had walked along it for many days, and they never go out except by night. And in order to prevent their eating the trees which they injure, a ring of mud is put around their bases and filled with water, and if the water dries up during the day, or if a straw falls across it in the night they have spies who notify them at once, and immediately such a multitude of them crosses over on the straw that before morning they have all the leaves on the ground; . . . and while everything grows here that can be desired, this curse interferes to such an extent that it takes away men's desire to plant any more than that without which they can not live."

A late and thoroughly trustworthy writer says of the ants in the coffee regions:

"The enemy most dreaded in the fazendas is indubitably the sauva, or tanajura, a dark-brown ant, two centimeters long, which undermines the ground by digging extensive passages and dens in all directions. It attacks all sorts of trees, the coffee-shrub among others, but has a decided preference for the orange and citron trees in the coffee gardens.

"In former times these ants seem to have worked frightful havoc in the cafesaes (coffee plantations) by causing landslips, because the means of destroying whole nests at once was not then discovered. Now they are less feared, although it still costs from 8 to 12 guineas a month per plantation to keep them down.

"On every fazenda two or three slaves are kept, whose exclusive business it is to find out the nests of the sauvas. Frequently they are even paid a certain sum to encourage and quicken their zeal. . . .

"The subterranean ant-labyrinth destroyed in my presence near the fazenda areas in Cantagallo seemed to be very extensive."[16]

The expense of fighting these ants is a really serious item in the cost of the production of Brazilian coffee. A distinguished Brazilian planter says, with perfect justice, that "among the obstacles with which the planters have to contend . . . there stands perhaps in the front rank the destructive force represented by the *saúba*."[17]

One can get some idea of the economic importance of ants in Brazil from the fact that in the 70's and early 80's an enormous number of privileges or patents were asked of the Brazilian government for machines and devices of various kinds for killing ants, and especially the *saúbas*.

[16] C. F. Van Delden Laërne: Brazil and Java. Report on coffee culture in America, Asia, and Africa, pp. 297-298. London, 1885.

[17] Henrique de Paula Mascarenhas: Revista Agricola do Imperial Instituto, vol. xiv, p. 215. Rio de Janeiro, December, 1883.

In 1857 the province of Rio de Janeiro voted a reward of $25,000 for the discovery of a means of destroying *saúbas.*[18]

The growing of oranges, roses, and other flowering plants is similarly interfered with in many places because of the cutting and carrying away of the leaves by the *saúbas.*

It is impossible to keep things out of their reach on any large scale. Certain devices are used with more or less success for protecting things indoors when they are constantly watched, but standing crops or considerable stores require constant watchfulness and war.

Bates has the following in regard to the *saúbas* in the Amazon region:

"This ant (the *saúba*) is seen everywhere about the suburbs, marching to and fro in broad columns. From its habit of despoiling the most valuable cultivated trees of their foliage, it is a great scourge to the Brazilians. In some districts it is so abundant that agriculture is almost impossible, and everywhere complaints are heard of the terrible pest."[19]

At another place (page 11) he says:

"Besides injuring and destroying young trees by despoiling them of their foliage, the *saúba* ant is troublesome to the inhabitants from its habit of plundering the stores of provisions in houses at night, for it is even more active by night than in the daytime. At first I was inclined to discredit the stories of their entering habitations and carrying off grain by grain the farinha, or mandioca meal, the bread of the poorer classes of Brazil. At length, while residing at an Indian village on the Tapajos, I had ample proof of the fact. One night my servant woke me three or four hours before sunrise by calling out that the rats were robbing the farinha baskets, the article at that time being scarce and dear. I got up, listened, and found the noise very unlike that made by rats, so I took the light and went into the storeroom, which was close to my sleeping place. I there found a broad column of saûba ants, consisting of thousands of individuals, as busy as possible, passing to and fro between the door and my precious baskets" (p. 12). "My servant told me that they would carry off the whole contents of the two baskets (about two bushels) in the course of the night if they were not driven off."

ATTACKS ON MAN

The *formiga de fogo*, or fire ants, are so called on account of the painfulness of their sting. When they are met with in large numbers there is simply no withstanding them.

One of the reasons for calling ants the kings, rulers, and owners of the country is due to the vicious attacks they make upon all kinds of animals. Bates tells of one case in which a town on the Tapajos was actually

[18] Auxiliador da Industria Nacional, vol. xxxvii, p. 64. Rio de Janeiro, 1869.
[19] H. W. Bates: The naturalist on the River Amazons, 4th ed., p. 9. London, 1875.

depopulated by ants of this kind. This statement seems so remarkable that it is quoted here at length:[20]

"Aveyros was deserted a few years before my visit on account of this little tormentor (*formiga de fogo*), and the inhabitants had only recently returned to their houses, thinking its numbers had decreased. It is a small species, of a shining reddish colour, not greatly differing from the common red stinging ant of our own country (*Myrmica rubra*), except that the pain and irritation caused by its sting are much greater. The soil of the whole village is undermined by it; the ground is perforated with the entrances to their subterranean galleries, and a little sandy dome occurs here and there, where the insects bring their young to receive warmth near the surface. The houses are overrun with them; they dispute every fragment of food with the inhabitants, and destroy clothing for the sake of the starch. All eatables are obliged to be suspended in baskets from the rafters and the cords well soaked with copauba balsam, which is the only means known of preventing them from climbing. They seem to attack persons out of sheer malice; if we stood for a few moments in the street, even at a distance from their nests, we were sure to be overrun and severely punished, for the moment an ant touched the flesh he secured himself with his jaws, doubled in his tail, and stung with all his might. When we were seated on chairs in the evenings in front of the house to enjoy a chat with our neighbors, we had stools to support our feet, the legs of which, as well as those of the chairs, were well anointed with the balsam. The cords of hammocks are obliged to be smeared with the balsam in the same way to prevent the ants from paying sleepers a visit."

In order to give a clear understanding of the seriousness of the bite of these ants, I quote the following from Dr. Richard Spruce's personal experience of them:

"Aug. 15, 1853.—Yesterday I had the pleasure for the first time of experiencing the sting of the large black ant called tucandera in Lingoa Geral. . . .

"I had gone after breakfast to herborise in the caapoera north of San Carlos, where there were a good many decayed trunks and stumps. I stooped down to cut off a patch of a moss on a stump, and remarked that by so doing I exposed a large hollow in the rotten wood; but when I turned me to put the moss into my vasculum I did not notice that a string of angry tucanderas poured out of the opening I had made. I was speedily made aware of it by a prick in the thigh, which I supposed to be caused by a snake until, springing up, I saw that my feet and legs were being covered by the dreaded tucandera. There was nothing but flight for it, and I accordingly ran off as quickly as I could among the entangling branches, and finally succeeded in beating off the ants, but not before I had been dreadfully stung about the feet, for I wore only slippers without heels, and these came off in the struggle. I was little more than five minutes' walk from my house. . . . and I wished to walk rapidly, but could not. I was in agonies, and had much to do to keep from throwing

[20] Naturalist on the Amazons, p. 205.

myself on the ground and rolling about, as I had seen the Indians do when suffering from the stings of this ant. I had in my way to cross a strip of burning sand, and then to wade through a lagoon, partly dried up, and not more than two feet deep. Both these increased the torture; I thought the contact with the water would have alleviated it, but it was not so.

"When I reached my house I immediately had recourse to hartshorn. No one was near but an Indian woman, . . . and she, without my telling her, . . . bound a ligature tightly above each ankle. After rubbing for some time with the hartshorn and experiencing no relief, I caused her to rub with oil, and then with oil and hartshorn mixed. None of these seemed to have any effect; when the oil was made hot it relieved me a little, but very little, indeed, and the wounds which were least rubbed ceased to pain me the soonest, one that had not been touched being the first cured.

It was about 2 p. m. when I was stung, and I experienced no alleviation of the pain till 5. During all this time my sufferings were indescribable. I can only liken the pain to that of a hundred thousand nettle-stings. My feet and sometimes my hands trembled as though I had the palsy, and for some time the perspiration ran down my face from the pain. With difficulty I repressed a strong inclination to vomit. I took a dose of laudanum at 4, and I think this did more than anything to lull the pain. I had been stung on the two big toes and on the soles of my feet, but the stings that caused me most suffering were four close together among the fine veins below the left ankle. When the pain of all the others had subsided this continued to torment me, and pains shot from it all over the forefoot and some way up the leg, notwithstanding the bandages.

"After the pain had become more bearable, it returned with great force on two occasions, at 9 o'clock and at midnight, when I stepped out of my hammock on my left foot, and each time caused me an hour of acute suffering. Towards morning I slept, and when I woke up I felt no inconvenience beyond a slight numbness in the feet, but the inflammation continued unabated for thirty hours. It is curious that nothing was visible externally more than would be caused by the stinging of an ordinary nettle. Possibly swelling was prevented by the application of the hartshorn and oil, for I have heard of cases where the swelling was considerable. Rubbing in the ingredients served to increase the pain both at the time and afterwards."[21]

BENEFICIAL ANTS

Not all the ants are to be looked upon as pests. Certain carnivorous ants are rather to be regarded as beneficial to agriculture, and to mankind generally, on account of their destruction of caterpillars and other noxious insects. In districts where cotton is grown the larvæ of the cotton moths are kept in check by the ants destroying the young ones, especially during the early part of the season. The invasion of houses by ant colonies is a common occurrence in every part of Brazil. Ordinarily these invasions are only temporary. During the hour or two when these

[21] Richard Spruce: Notes of a botanist on the Amazon and Andes, vol. I, pp. 362-364. London, 1908.

ants swarm through one's house or rooms they are certainly annoying, but they soon disappear, and one feels that he has been relieved to a considerable extent from the cockroaches and other more offensive and serious plagues.

Many writers have described the operations of these ants, but the following, quoted from Dr. Richard Spruce, will give a clear idea of these operations:[22]

"Ecitons, or foraging ants (called Cazadoras in Peru), seem to be true wandering hordes, without a settled habitation, for a certain number of them may always be seen carrying pupæ, apparently of their own species; but they sojourn sometimes for several days whenever they come upon suitable food and lodging.

"The first time I saw a house invaded by Cazadoras was in November, 1855, on the forest slope of Mount Campana, in the eastern Peruvian Andes. I had taken up my abode in a solitary Indian hut, at a height of 3,000 feet, for the sake of devoting a month to the exploration of that interesting mountain. The walls of the hut were merely a single row of strips of palm trees, with spaces between them wide enough to admit larger animals than ants. One morning soon after sunrise the hut was suddenly filled with large blackish ants, which ran nimbly about and tried their teeth on everything. My charqui proved too tough for them; but they made short work of a bunch of ripe plantains, and rooted out cockroaches, spiders, and other such like denizens of a forest hut. So long as they were left unmolested they avoided the human inhabitants; but when I attempted to brush them away they fell on me by hundreds and bit and stung fiercely. I asked the Indian's wife if we had not better turn out a while and leave them to their diversions. 'Do they annoy you?' said she. 'Why, you see it is impossible for one to work with the ants running over everything,' replied I. Whereupon she filled a calabash with cold water, and, going to the corner of the hut where the ants still continued to stream in, she devoutly crossed herself, muttered some invocation or exorcism, and sprinkled the water gently over them. Then walking quietly round and round the hut, she continued her aspersion on the marauders, and thereby literally so damped their ardour that they began to beat a retreat, and in ten minutes not an ant was to be seen.

"Some years afterwards I was residing in a farm-house on the River Daule, near Guayaquil, when I witnessed a similar invasion. The house was large, of two stories, and built chiefly of bamboo-cane, the walls being merely an outer and an inner layer of cane, without plaster inside or out, so that they harboured vast numbers of cockroaches, scorpions, rats, mice, bats, and even snakes, although the latter abode chiefly in the roof. Notwithstanding the size of the house, every room was speedily filled with the ants. The good lady hastened to fasten up her fresh meat, fish, sugar, etc., in safes inaccessible even to the ants, and I was prompt to impart my experience of the efficacy of baptism by water in ridding a house of such pests. 'Oh!' said she, laughingly, 'we know all that; but let them first have time to clear the house of vermin.

[22] Richard Spruce: Notes of a botanist on the Amazon and Andes, vol. ii, pp. 371-373. London, 1908.

for if even a rat or snake be caught napping they will soon pick his bones.' They had been in the house but a very little while when we heard a great commotion inside the walls, chiefly of mice careering madly about and uttering terrified squeals; and the ants were allowed to remain thus and hunt over the house at will for three days and nights, when, having exhausted their legitimate game, they began to be troublesome in the kitchen and on the dinner table. 'Now,' said Dona Juanita, 'is the time for the water cure,' and she set her maids to sprinkle water over the visitors, who at once took the hint, gathered up their scattered squadrons, reformed in column, and resumed their march. Whenever their inquisitions became troublesome to myself during the three days, I took the liberty to scatter a few suggestive drops among them, and it always sufficed to make them turn aside; but any attempt at a forcible ejectment they were sure to resent with tooth and nail, and their bite and sting were rather formidable, for they were large and lusty ants. For weeks afterwards the squeaking of a mouse and the whirring of a cockroach were sounds unheard in that house." (Footnote.)

"The ants called Carniceras, or butchers, in Maynais are probably of a tribe distinct from the foragers, for they are burrowing ants, and are said to prefer the flesh of human carcasses to any other food. Padre Velasco, in his *History of Quito*, assures us that they will make a perfect skeleton of a corpse the very day it is buried, and that they devour any disabled animal, however large, they find in the forest."

Thomas Belt has a good deal on the swarms of ants in Central America. The following extract is from his "Naturalist in Nicaragua," page 17:

"One of the smaller species (*Eciton predator*) used occasionally to visit our house and swarm over the floors and walls, searching every cranny and driving out the cockroaches and spiders, many of which were caught, pulled, bitten to pieces, and carried off. The individuals of this species were of various sizes, the smallest measuring one and a quarter lines and the largest three lines, or a quarter of an inch.

"I saw many armies of this, or a closely allied species, in the forest. My attention was generally first called to them by the twittering of some small birds, belonging to several different species, that follow the ants in the woods. On approaching, a dense body of the ants, three or four yards wide, and so numerous as to blacken the ground, would be seen moving rapidly in one direction, examining every cranny and underneath every fallen leaf. On the flanks and in advance of the main body smaller columns would be pushed out. These smaller columns would generally first flush the cockroaches, grasshoppers, and spiders. The pursued insects would rapidly make off, but many in their confusion and terror would bound right into the midst of the main body of ants."

Bates has the following regarding the Ecitons (page 354):

"One or other of them is sure to be met with in a woodland ramble, and it is to them, probably, that the stories we read in books on South America apply of ants clearing houses of vermin, although I heard of no instance of

their entering houses, their ravages being confined to the thickest parts of the forest.

"When the pedestrian falls in with a train of these ants, the first signal given him is a twittering and restless movement of small flocks of plain-colored birds (ant thrushes) in the jungle. If this be disregarded until he advances a few steps farther, he is sure to fall into trouble, and find himself suddenly attacked by numbers of the ferocious little creatures. They swarm up his legs with incredible rapidity, each one driving its pincer-like jaws into his skin, and with the purchase thus obtained, doubling in its tail, and stinging with all its might. There is no course left but to run for it; if he is accompanied by natives, they will be sure to give the alarm, crying, 'Tauóca!' and scampering at full speed to the other end of the column of ants. The tenacious insects who have secured themselves to his legs then have to be plucked off one by one, a task which is generally not accomplished without pulling them in twain, and leaving heads and jaws sticking in the wounds.

"The errand of the vast ant armies is plunder, as in the case of Ecitón legions; but from their moving always amongst dense thickets, their proceedings are not so easy to observe as in that species. Wherever they move, the whole animal world is set in commotion, and every creature tries to get out of their way. But it is especially the various tribes of wingless insects that have cause for fear, such as heavy-bodied spiders, ants of other species, maggots, caterpillars, larvæ of cockroaches, and so forth, all of which live under fallen leaves or in decaying wood. The Ecitons do not mount very high on trees, and therefore the nestlings of birds are not much incommoded by them.

"The armies never march far on a beaten path, but seem to prefer the entangled thickets, where it is seldom possible to follow them. I have traced an army sometimes for half a mile or more, but was never able to find one that had finished its day's course and returned to its hive. Indeed, I never met with a hive; whenever the Ecitons were seen they were always on the march" (p. 355).

ANTS AS FOOD

In the Amazon region some of the ants are even used by the Indians for food.

"I have many times seen Indians eat the *saúba* ant (called *bachâco* in Venezuela). The large kinds only are eaten, and at those times when the bachacos pour from their holes in great numbers (probably sending forth colonies after the manner of bees), if it be near any pueblo, all the unoccupied Indians in the place turn out to collect them. The head and thorax are the parts eaten, the abdomen being nipped off (at San Carlos I constantly see them eaten entire), and it is eaten uncooked. The taste to me is strong, fiery, and disagreeable, but those who have eaten the bachâco fried in turtle oil tell me it is quite palatable."[23]

In the more thickly settled parts of Brazil the custom of eating these ants is either not practiced nowadays, or, if it is, it is not generally known.

[23] Richard Spruce: Notes of a botanist on the Amazon and Andes, vol. 1, p. 484. London, 1908.

In the early history of the country, however, when the native Indians were much more abundant than they are now, the custom appears to have been common. Gabriel Soares de Souza, after living 16 years in Bahia, wrote as follows in 1587:[24]

"There are in this same country other ants which the Indians call *içans*, and which have bodies the size and color of an Alicante raisin . . . which live on the leaves of trees and worms and other small animals they find on the ground; these ants the Indians eat roasted over the fire, and they are greatly enjoyed; and some white men who live amongst them and the half-breeds regard them as good food, and boast of it as being very savory; . . . and when roasted they are white on the inside."

Orton[25] says the *saúbas* "are eaten by the Rio Negro Indians, and esteemed a luxury, while the Tapajos tribes use them to season their mandioca sauce."

STRUCTURES ABOVE GROUND

Origin of the structures.—The word "nests" frequently applied to the superficial structures of ants should not be understood to mean nests in the ordinary signification of the word. These structures sometimes contain the queens, eggs, and larvæ, but at other times these are kept in excavations below the surface.

The mounds made by the true ants all begin as small funnel-shaped ridges around the excavations started by individual females. The large mounds are the results of the work of many generations and of a vast number of individuals.

Without going into any detailed description of the habits of the ants, it is worth while to give, for those unfamiliar with their habits, a general idea of the methods followed by these ants in establishing new colonies and in increasing them. When the swarming or mating season of the *saúba* ants comes, the young females leave their homes and fly away. They seem to fly about very much at random—at least, I have rarely seen them going in any particular direction—and when they have been seen going together it was apparently due to the direction of the wind or the position of the sun at the time, rather than to any definite purpose on their part.

When the female alights after a flight of only a few minutes, she breaks off her wings and at once falls to work at excavating a burrow. All kinds of places are selected for these burrows. It does not appear that the selection is deliberate, but it seems to be determined by the acci-

[24] Gabriel Soares de Souza: Tratado descriptivo do Brazil em 1587. Revist. Inst. Hist. do Brazil, vol. xiv, pp. 273-274. Rio de Janeiro, 1851.

[25] James Orton: The Andes and the Amazon, 3d ed., p. 301. New York, 1876.

dent of alighting from an aimless flight. Judging from the large number of individual females I have frequently seen in the air and on the ground at one time, the great majority of these young colonies must fail to survive. Often I have seen the young females so abundant that there must have been an individual to every square meter of land surface over areas of many hundreds of acres.

In some places where the new arrivals alight the mounds are already so thick that there is little or no room for new colonies, and it is probable that some of these young females must either be adopted into the old colonies or they are killed or die.[26]

It is evident from the nature of the case that where such a large number of new colonies is started most of them must perish from mere overcrowding, if for no other reason.

The excavation first made by a young female is small and simple, and the earth taken from it is heaped about the opening without any apparent order. Doctor Huber, in the paper just cited, states that at Para, in a colony started by a single female, the first workers appear at the end of 40 days. Shortly thereafter the queen, or founder of the colony, ceases to be an active worker, and all subsequent excavating is done by the constantly increasing number of workers. As the colonies increase in numbers more underground room is required, and the amount of earth excavated and carried to the surface increases proportionately. This earth is brought to the surface in the form of small pellets in the jaws of the workers, and are thrown down apparently without any other object than to be rid of them. Sometimes they are heaped up in funnel-shaped pits; sometimes they are thrown out on the downhill side of the opening. At first these bits of earth form heaps of loose, incoherent material, but in time, and with rain and sunshine, it packs down until it is often as hard as an unbaked brick. As long as the colony is active and growing, additions are constantly being made to these accumulations, and these additions may be at any point over the sides or at the top. Passageways are either kept open through these heaps of earth or they are reexcavated. This is demonstrated by digging into the mounds; but it is evident without opening them, from the fact that the fresh material is brought out and spread over any and all parts of the surface.

Size of the mounds.—It might be inferred that there would be practically no limit to the size of the mounds built in this fashion, and I am not sure that there are any limits save those which may be imposed by

[26] Just how new colonies of saubas can be established by a single female is described by Dr. J. Huber, in Biologisches Centralblatt, vol. xxv, pp. 606-618, 624-635, and in the Boletim do Museu Goeldi, vol. v, pp. 223-241. Pará, 1907-8. Also in the Annual Report of the Smithsonian Institution for 1906, pp. 355-367.

certain physical conditions, such as the amount and distribution of the rains, the character of the soil, the area over which the necessary plants or food can be obtained, etcetera. Of course, the mounds are of different sizes according to their ages; but considering only the largest and oldest ones made by a single species, and found in various different localities, it is noteworthy that there is a great difference in the sizes of the largest of them. Just what determines this variation I can not say positively, but the influences referred to above—that is, rainfall, character of soil, and vegetation—naturally suggest themselves as possible influences.

Bates has the following in regard to the mounds made by the *saúbas* in the vicinity of Para:[27]

"In our first walks we were puzzled to account for large mounds of earth, of a different colour from the surrounding soil, which were thrown up in the plantations and woods. Some of them were very extensive, being forty yards in circumference, but not more than two feet in height. We soon ascertained that these were the work of the saúbas, being the outworks, or domes, which overlie and protect the entrances to their vest subterranean galleries. On close examination, I found the earth of which they are composed to consist of very minute granules, agglomerated without cement, and forming many rows of little ridges and turrets. The difference in colour from the superficial soil of the vicinity is owing to their being formed of the undersoil, brought up from a considerable depth. It is very rarely that the ants are seen at work on these mounds; the entrances seem to be generally closed; only now and then, when some particular work is going on, are the galleries opened."

Nowhere do I remember to have seen more or larger ant-hills than along Rio Utinga, in the diamond regions of the interior of the State of Bahia. From the town Riachão, down the river to the village of Pegas, the examples are big and abundant. In a few places they are so close together that, big and little, they appear to cover half of the ground. My notes, written on the spot, say "more than half of the ground." Such places, however, are exceptional. The distribution is always more or less irregular—bunched apparently on account of characteristics of soil or drainage, or for some other reason that does not appear. In some areas of from 10 to 20 acres the ant-hills occupy from a fifth to a third of the ground, while over larger tracts they take up from one-eighth to a seventh of the ground. In height the mounds are often as much as 5 meters high, with bases 15 or 16 meters in diameter. In the forests these mounds are generally overgrown with young trees. On many of the big mounds I have seen trees more than 30 centimeters in diameter. At the village of Antonio José the people have planted pineapples upon the mounds.

[27] Naturalist on the River Amazons, 4th ed., p. 10. London, 1875.

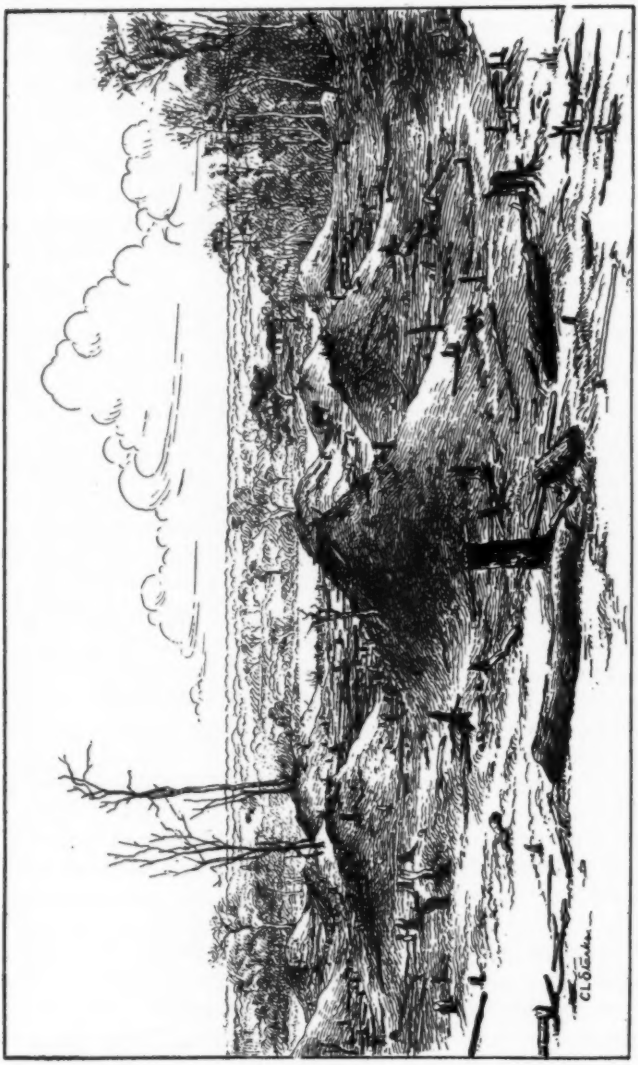

FIGURE 1.—*Ant-hills on Rio Utinga, near the Village of Pegas, State of Bahia*

From a photograph by R. Crandall, 1907

At fazenda Bello Horizonte, about 18 kilometers north of the village of Pegas, the ant-hills are so large and stand so thickly upon the ground that they form one of the most striking illustrations I have ever seen of the work of these insects. An area of some 30 acres or more is there covered with mounds resembling haycocks. They probably average 2 meters in height and a diameter of 4 or 5 meters at the base.

At a place called Ponte Nova, on Rio Utinga, 8 kilometers north of the village of Pegas, the ant-hills are a remarkable feature of the landscape. To the east and northeast of the Protestant college the mounds

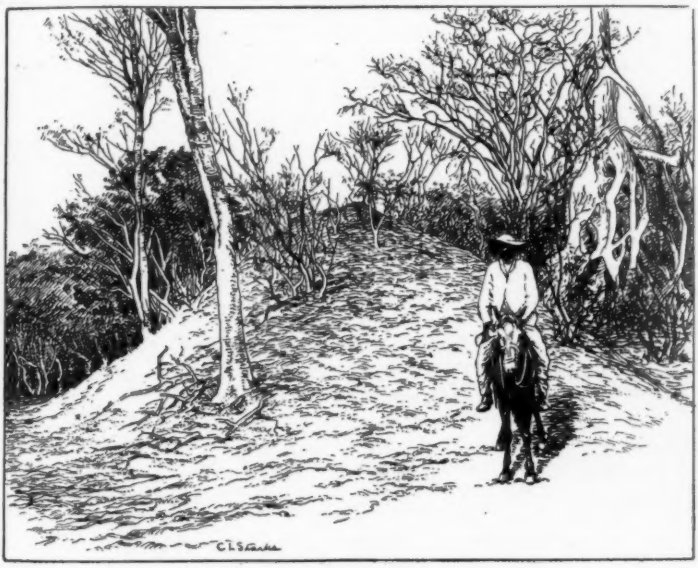

FIGURE 2.—*Ant-hill (Formiga de mandioca) near Mundo Novo, State of Bahia, Brazil*
From a photograph by R. Crandall, 1907

cover the old fields. One of the accompanying photographs (figure 2, plate 35) and figure 1 were made in this region.

In the region south of Morro do Chapeo, in the State of Bahia, they are equally large on the clayey soils derived from the Caboclo shales.

The accompanying illustrations were made from photographs taken near Mundo Novo and Ventura, in that area.

Farther east in the State of Bahia, in the vicinity of Serrinha, a station on the São Francisco Railway, the ant-hills are large and abundant.

From a photograph by R. Crandall, 1907

Six kilometers north of the station one was found by measurement to be 1.8 meters high and 4.5 + meters wide at the base. This mound was not regarded by the people of the locality as anything unusual.

To the east of Serrinha several mounds were observed with a height of 3 meters and a diameter at the base of 10 meters. These mounds, therefore, contain each 78.5 cubic meters of earth.

At and about Catuny, a station on the São Francisco Railway, the ant mounds are notably abundant, and many of them have a height of 1.5 meters.

FIGURE 3.—*Ant-hills made by the "Formiga de mandioca," near Ventura, State of Bahia, Brazil*

From a photograph by R. Crandall, 1907

Along the western half of the Bahia and Minas Railway, that starts from the coast near Caravellas, in the southern part of the State of Bahia, and runs west 376 kilometers into the State of Minas Geraes, ant-hills are big and abundant. The newer ones are steeply conical, but with age they become more or less rounded and flattened. In the vicinity of Urucú Station (kil. 226) the mounds are so thick and so close together that the country looks like a field of gigantic potato hills.

In some places they stand so close that their bases touch each other, though such cases appear to be rather exceptional. The mounds in this

part of Minas and Bahia that appear to have reached their full development range from 1 to 4½ meters in height and from 3 to 10 meters in diameter at the base. The biggest of these mounds—that is, one 4.5 meters high and 10 meters in diameter—contains approximately 117 cubic meters of earth.

Mention has already been made of the abundance and size of the mounds in some parts of the Rio Utinga region, in the interior of Bahia. At one place in this region, where the forests had been cleared away so that the mounds were clearly visible, I selected a spot where they were strikingly abundant, and measuring a space 100 by 100 meters, as nearly as it could be done by pacing, counted the mounds within the area and estimated their heights and diameters at the base.

The slopes of these mounds vary from less than 30 degrees up to 47 degrees, and on some parts of them there are even perpendicular places. It was thought that 38 degrees was a fair average for the ones in this particular area.

The figures obtained are given in the table below:

Table of Areas and cubical Contents of Mounds of different Sizes within an Area of 10,000 square Meters.

(All measurements are in meters.)

Number of mounds.	Diameter of base.	Area of each in square meters.	Total area in square meters.	Height.	Cubical contents.	Total contents in cubic meters.
1	15	176.71	176.71	4.5	265	265
2	11	95.03	190.06	4.2	133	266
6	10	78.54	471.24	3.9	102	612
8	8	50.26	402.08	3.1	51	408
12	7	38.48	460.76	2.9	37	444
5	6	28.27	141.35	2.3	21	105
4	5	19.63	78.52	2.0	13	52
7	4	12.56	87.92	1.7	7	49
8	3	7.06	56.48	1.2	3	24
Totals, 53	.....	.....	2,064.82	.....	.....	2,225

This estimate makes the area actually covered by the mounds close to one-fifth of the total area under consideration. My notes show that within areas of a few acres the ground covered by the mounds is sometimes as high as one-half of the total area. The cubical contents of the mounds, if evenly distributed over the entire 10,000 square meters, would have a thickness of 22.25 centimeters.

Although the mounds within the area here considered were large, they were not the biggest I have seen, nor do they average as large as can be

found. The largest ones measured were on the upper drainage of Rio Utinga; several of these were found to be 5 meters high and 16 and 17 meters in diameter at the base, and each contained, therefore, about 340 cubic meters of earth. There were no other mounds closer to these than 10 or 15 meters.

M. Gounelle, a French entomologist, has calculated from a photograph the size of some of the Bahia mounds. Following is a translation of a part of his article. The mounds mentioned by him are near Condeuba, which is in the southern part of the State:[28]

"A photograph shown to the Society makes it possible for one to appreciate the enormous amount of work done by certain ants, and to measure fairly well the volume of the materials moved by them in digging their galleries. This photograph, taken in the vicinity of the little city of Condeuba, in the southern part of the State of Bahia, shows a clearing in which appear five conical nests of an ant, probably *Oecodoma cephalotes* Latreille.[29] The five cones have about the same dimensions. One notes in the foreground that the scale is one centimetre to the metre, as is readily seen by comparison with the man standing on top of the mound. Its diameter is 16 metres and its height is 4.5 metres, which by a simple calculation gives 301 cubic metres for its volume and 1,500 cubic metres for the total volume of the five mounds. The clearing has a surface of about one hectare, so that the earth of the five mounds, if spread evenly all over it, would have a thickness of 15 centimetres. . . . It should be added that the building of ant-hills of this size within a limited area is not an isolated case. The traveller in these regions meets with them everywhere, and that, too, over an enormous extent of country."

The reader should be reminded just here that this sort of thing is not to be seen in all parts of the country, by any manner of means. So far as my own observations go, ant mounds are unusually large and unusually abundant in this particular part of Brazil.

Age of the mounds.—The amount of work done by these ants in a region where they seem to be favorably located is fairly well shown in the preceding table. Trustworthy data for calculating the time required to build a mound of a given size or to do any given amount of work is lacking. Necessarily the time must vary with the size of the colonies, other things being equal. The colonies, however, appear to have their ups and downs, for while some of them increase in numbers and continue to add to the mounds for long periods, others appear to be less active, while still others disappear, whether by migrating or through the death or captivity of the members is not certainly known at present. It is interesting to note that the Brazilians generally regard the size of the ant-hill as

[28] E. Gounelle: Transport de terres effectué par des fourmis au Brésil. Annales de la Société Entomologique de France, 7me sér., no. 6, pp. 332-333. Paris, 1896.

[29] This is the name of the so-called *sauba*. J. C. B.

directly related to the age of the colony. At Serrinha, on the São Francisco Railway, I was told that mounds about 2 meters high and having a base of about 5 meters were probably as much as a hundred years old. This was an expression of views based simply upon a general impression and not upon records.

M. Gounelle[30] says in regard to the age of ant-hills:

"The age of these ant-hills is rather difficult to determine; however, the curate of the city mentioned above (Condeuba, Bahia) has assured me that three nests like those in the photograph, located at the entrance to the cemetery, were not more than one metre high when he went to that country, about sixty years ago. Taking a hundred years as an average for the building of these gigantic ant-hills, it does not seem rash to suppose that in these regions the soil must have been worked over by the ants to a certain depth several times in the course of geologic periods."

UNDERGROUND WORK

So far as I can learn, there has never been any careful examination or study of the character, extent, and uses of the underground excavations made by ants in the tropics. What is known about them has been learned accidentally, and our knowledge of the passages is, therefore, fragmentary. I have frequently dug into the mounds, but always without the time necessary for satisfactory results. The most I have been able to make out in these hasty explorations is that the superficial mounds are penetrated in every direction with passageways. The large mounds were in no case opened down to the original surface of the ground; but when small mounds were opened they were found to connect through small tunnels with the underground excavations.

A pit started by the removal of a large ant-hill east of Timbo, in the interior of Bahia, and continued to a depth of about 4 meters, showed the arrangement of the underground tunnels better than I have seen it elsewhere. The section did not pass through the main shaft or tunnel that connected the ant-hill with the subterranean excavations, but a little to one side of it. The upper layer of the earth, to a depth of half a meter, was undisturbed; then there was one tunnel with a flat floor, about 20 to 25 centimeters across, and having a low arched roof; below this, at a distance of about 25 centimeters, were two tunnels at the same level and of about the same size and shape; below these, at a further depth of about 25 centimeters, were three similar openings. This arrangement continued to a depth of nearly two meters, the tunnels being more numerous always at the lower levels. The tunnels at the lowest

[30] E. Gounelle: Transport de terres effectué par des fourmis au Brésil. Bull. Soc. Entomologique de France. 7me sér., no. 6, p. 332. Paris, 1896.

level did not form a complete row, but the work seemed to have been commenced at the outside.

This same arrangement of the tunnels has been seen frequently in railway cuts and ditches, but nowhere else have I seen so many levels or such a clearly defined plan in the placing of the excavations.

In some other cases noted the number of tunnels connecting the above-ground mounds with the underground galleries seemed to vary with the size of the mounds—that is, the more ground the mound covered, the more passageways there seemed to be to connect with the galleries beneath.

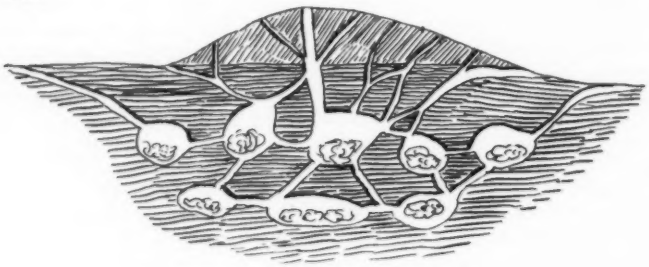

FIGURE 4.—*Nest of leaf-cutting Ant*
After Belt. "The Naturalist in Nicaragua," p. 80

Bates gives the following regarding the *saúbas*.[31]

"The entrances are small and numerous; in the large hillocks it would require a great amount of excavation to get at the main galleries; but I succeeded in removing portions of the dome in smaller hillocks, and then I found that the minor entrances converged, at the depth of about two feet, to one broad, elaborately worked gallery, or mine, which was four or five inches in diameter."

The section through the burrows given by Belt is reproduced in figure 4. This section, however, is diagrammatic, and does not claim to show the great extent of the galleries. Belt tells, however, of galleries 1.5 meters in depth (page 76). The best evidence I have been able to gather in regard to the depth to which the ants penetrate has been obtained in cuts along railways and canals, and in deep ditches often dug to serve as fences. On Rio do Peixe, near Serro, in the State of Minas Geraes, I found the galleries as deep as 2.5 meters at several places along a canal under construction. Most of them, however, were only about 1.5 meters below the surface at the deepest points exposed. At Bomfim, on the

[31] H. W. Bates: The Naturalist on the Amazons.

Bahia and São Francisco Railway, I found the burrows exposed in a deep ditch at a depth of 2.1 meters.

Sampaio, a Brazilian entomologist who has given much attention to the *saúba* ants, shows one burrow as much as 3.5 meters below the surface.[32]

In the State of São Paulo, Brazil, the coffee planters have among their employees men whose business it is to fight the *saúbas*. These ant-killers, in the course of their operations against the ants, are said to open out sometimes their underground excavations to a depth of 3.6 meters.

Dr. Jaoquim Lustosa, a Brazilian mining engineer of Lafayette, State of Minas Geraes, Brazil, writes me (June 16, 1909) as follows in regard to the depth to which ants burrow in Minas: "Competent persons assure me that the true ants burrow to a depth of 10 metres or more, and that they exhibit a strange and remarkable intelligence, and that they even cross wide and deep streams by means of tunnels so deep as to avoid the infiltration of the water."

The length of the tunnels has often been demonstrated by forcing smoke through them. I have myself seen fumes blown into one opening and issuing from others as much as 300 meters away. Mr. Charles J. Dulley, a civil engineer of São Paulo, informs me that he has seen fumes driven into the chief nucleus of a colony of *saúbas*, and issuing 183 meters away.

The following statement is given in Mrs. Agassiz's book:[33]

The *saúbas*

"make houses by excavating, and sometimes undermine a hill so extensively with their long galleries that when a fire is lighted at one of the entrances to exterminate them, the smoke issues at numerous openings, distant perhaps a quarter of a mile from each other, showing in how many directions they have tunneled out the hill, and that their winding passages communicate with each other throughout."

On the authority of Rev. H. Clark, Bates says[34] that ants

"excavated a tunnel under the bed of the River Parahyba, at a place where it is as broad as the Thames at London Bridge. At the Magoary rice mills, near Pará, these ants once pierced the embankment of a large reservoir; the great body of water which it contained escaped before the damage could be repaired. In the Botanic Gardens at Pará, an enterprising French gardener tried all he could think of to extirpate the saúba. With this object he made fires over

[32] A. G. de Azevedo Sampaio: Sauva ou Manhu-uára, pp. 22, 52, 64. Sao Paulo, 1894.
[33] Prof. and Mrs. Louis Agassiz: A journey in Brazil, p. 105. Boston, 1868.
[34] H. W. Bates: Naturalist on the Amazons, 4th ed., pp. 9-15. London, 1875.

some of the main entrances to their colonies, and blew the fumes of sulphur down the galleries by means of bellows. I saw the smoke issue from a great number of outlets, one of which was 70 yards distant from the place where the bellows were used. This shows how extensively the underground galleries are ramified."

Another writer, Rev. J. C. Wood, tells of the *saúbas* having

"ruined a gold mine for a time, breaking into it with a tunnel some 80 yards in length and letting in a torrent of water, which broke down the machinery and washed away all the supports, so that the mine had to be dug afresh."[35]

The diameter of an underground passage varies from 1 or 2 centimeters up to 5 centimeters or more. They widen out and narrow down without any apparent reason, and those made by the *saúbas* that have been examined have here and there local enlargements that are commonly from 1 to 2 decimeters in height and from 1 to 3 decimeters in length. These chambers, when freshly opened, I have generally found filled, or partly filled, with loose, mouldy masses of dead leaves.

Belt describes the underground passages in Nicaragua as follows:[36]

"In our mining operations we also, on two occasions, carried our excavations from below up through very large formicariums, so that all their underground workings were exposed to observation. I found their nests below to consist of numerous rounded chambers, about as large as a man's head, connected together by tunneled passages leading from one chamber to another."

RELATIONS TO THE SOIL

The distribution of ant colonies as shown by their mounds suggests, if it does not prove beyond question, that the character of the soil has an important influence on the distribution of the ants themselves. In view of the habits of ants, it seems highly probable that at the time of leaving their nests the young females scatter over the surrounding region pretty much at random. When they alight, some of them find themselves in locations where ant colonies, on account of the character of the ground, can not possibly survive, and as these young females break off their wings as soon as they alight, they can not renew their flight and seek more favorable ground, but they must perish without having founded a new colony. And this must happen over and over again, with the final result that localities unfavorable for ants do not have ant colonies, while the favorable localities may have a superabundance of them. Favorable and

[35] Charles Waterton: Wanderings in South America. Explanatory Index, Rev. J. G. Wood, p. 47. London, 1882.

[36] The Naturalist in Nicaragua, p. 80.

unfavorable conditions are not always sharply defined, but merge into each other.

In some cases it is quite evident what constitute unfavorable conditions. Ground that is constantly wet or liable to inundation can not be occupied; hard, rocky surfaces, or even very thin soils, are not available; soils so sandy or friable that underground tunnels dug in them will not stand are evidently not available for the establishment of colonies.

Between soils most favorable and unfavorable ones there are all sorts of gradations, so that one is prepared, for this reason alone, to find the ant-hills bigger and more abundant in some places than in others. It is evident that it is all a question of adaptability, however, rather than a matter of choice on the part of the ants.

Just what kind of soil is most favorable for the ants I can not state positively. My general impression is that the mounds are most abundant on clayey soils, whether the clay comes directly from the decomposition of feldspathic rocks or from the disintegration of shales and slates.

This preference for the clayey soils is well shown at many places through the diamond-bearing highlands of the interior of Bahia, where the diamond-bearing quartzites, known as the Lavras series, are underlain by a thick series of shales called the Caboclo (or Paraguassú ?) series. The Lavras beds being quartzites, or sandstones, break down into a very sandy soil, while the Caboclo shales form a stiff, clayey soil, and as they are adjacent to each other the line of demarcation between the two soils is usually well defined. While traveling through that district in 1907, I was frequently able to locate myself geologically by the abundance or absence of the ant-hills. Not infrequently the line of parting between the two series was concealed by a thick soil and overgrown with forests, but the distribution of the mounds would often show the line of parting within 20 or 25 meters.

My former assistant, Mr. Roderic Crandall, who has traveled extensively in Bahia, Pernambuco, Piauhy, Minas, and Goyaz, writes, in reply to my inquiries, as follows regarding the preference of the ants for certain soils: "In Bahia the ants of all kinds show a preference for the Estancia and Caboclo shales; next to these the granites seem to have the biggest nests." (Private letter; Rio, June 23, 1909.)

I infer that the smaller number of the mounds on the sandy soil is due to the fact that during the rainy season water soaks through into the burrows, and the excavations do not stand up where the soil is wet.

Thinking it possible that the exposure of the mounds or of the ground on which they stand to the sun might influence location and distribution, an outlook has been kept with these questions in mind. It does not

appear thus far that such exposure influences the location or size of the mounds, even in the southern part of Brazil, where the sun is on the north most or all of the year.

The White Ants, or Termites

General characteristics

The so-called white ants, or termites, belong to the *Isoptera*, and are therefore not ants at all. They are included in this paper solely on account of the geologic work done by them in the tropics, which bears a certain similarity to the geologic work of the true ants.

In Brazil the white ants are commonly known by the name of *cupim*. In their habits the white ants both resemble and differ from the true ants. They generally avoid the light, carrying on their work, even when it is above ground, in galleries which they construct as they go. Their nests are sometimes attached to tree trunks or rocks, but they are often built directly upon the ground. Not infrequently these nests are as large, or even larger, than the nests of the true ants, but they are very different in shape and character.

Abundance

Here, again, I am unable to give anything regarding the biology of the white ants.[37]

Dr. Fritz Muller, who lived for many years in southern Brazil, reports 15 or 16 species of termites in that part of the country, but not all of these live on or in the ground.

M. Jules Desneux, in his monograph on the Termitidæ, reports 45 species from Brazil and some 15 or more from other tropical parts of America.

White ants, like other animals, are not evenly distributed in the tropical parts of South America. They are so much less obtrusive and pugnacious, however, that they do not attract the attention as promptly as do the true ants.

Azara says he has seen these insects during the mating season filling the air for more than a mile.[38]

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[37] For the benefit of those who are interested in the biology of white ants I cite the following:

K. Escherich: Die Termiten oder weissen Ameisen. Eine Biologische Studie, vol. xii, p. 198. Leipsig, 1909.

Genera Insectorum publies par P. Wytsman. Fasc. 25, Isoptera, fam. Termitidæ par Jules Desneux. Bruxelles, 1904.

[38] Don Felix de Azara: Voyages dans l'Amérique Meridionale, t. i, p. 192. Paris, 1809.

The fact that the white ants live and work entirely under cover might naturally lead one to infer that they were much less abundant than the true ants. But nowhere have I found the ground as thickly covered with the termites' nests as with those of the true ants, a fact probably due to some extent to the methods by which the two kinds of insects procure their food supplies.

I have never been able to estimate the number of individuals in the old colonies, nor have I found such an estimate made by any one else. In the matter of numbers we are obliged to depend on general impressions gained from the abundance of the above-ground structures of the separate colonies and from certain of their habits. For example, it is stated that the queen of an allied species whose habits have been studied has "an egg-laying rate of 60 per minute, or something like 80,000 per day."[39]

Prince Maximilien, who traveled through the region between Rio and Bahia, says of their abundance: "One can get some idea of their prodigious numbers when he remembers the vast extent of the interior of Brazil, and of the number of the little animals that occupy these nests, when he reflects that one can not go 20 paces without meeting their mounds."[40]

This statement must be taken with certain allowances, for, as pointed out elsewhere, the nests are not everywhere equally abundant.

ANIMALS FEEDING ON TERMITES

As the white ants have no means of defense against their natural enemies, they are easily destroyed and are preyed on by many other insectivorous animals. Indeed, one of the impressive evidences of the great numbers of the white ants in South America is the existence there of certain large vertebrate burrowing animals that are said to feed almost exclusively upon the white ants.[41]

The great ant-eater, known in Brazil as the *tamanduá bandeira*, is said to live entirely on ants. Brazilians acquainted with the habits of the *tamanduá* tell me, however, that the ant-eater does not eat the *saúbas* or other biting or stinging ants, but that it lives chiefly and almost exclusively on the *cupim*, or so-called white ant. To give an idea of the size of the animal, I quote the following measurements of an ant-eater as given by Wells: Head, 16 inches; back, 4 feet; tail, 4 feet; total length, 9 feet 4 inches. He says it has no teeth.[42]

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[39] C. L. Marlatt: Circular 50, p. 3, 2d ser., Bureau of Entomology, U. S. Department of Agriculture. Washington, 1908.

[40] Maximilien, Prince de Wied-Neuwied: Voyage au Brésil, t. iii, p. 129. Paris, 1822.

[41] Holes often found in the mounds of the true ants show that some of these large ant-eating animals feed on the true ants also.

[42] J. W. Wells: Three thousand miles through Brazil, vol. ii, p. 141. London, 1886.

The existence of an animal as big as an ordinary dog, over 2 feet high at the shoulder, with its long, slender muzzle, its powerful forelegs and claws adapted to the excavation and exploration of ant-mounds, and its tongue nearly a yard in length, and living chiefly, if not entirely, upon white ants, is an important witness on the side of the abundance of termites in the region in which it lives. Bates reports four species of ant-eaters in the Amazonas region, two of which are large and two small ones (op. cit., 2d ed., p. 110), while Wallace says there are five species in tropical America, besides one extinct form.[43]

The armadillos, known in Brazil as *tatús*, are also ant-eaters. As Mr. Wallace points out,[44] the armadillos are highly characteristic of tropical South and Central America, and at the time of the publication of his famous work on the geographical distribution of animals they embraced 6 genera and 17 species, to say nothing of many extinct species found by Lund in the caves of Minas Geraes. Some of these armadillos are so large that a single individual will weigh as much as 70 pounds, or even more.

They live upon insects chiefly, and the white ants seem to be their favorite food. They enter the nests by digging openings at the base of the cones with their powerful fore feet.[45]

Gardner states that the white ants also form the principal food of the South American ostrich (*Rhea americana*), which is the largest bird in tropical America.[46]

In addition, there are large numbers of birds and reptiles, such as toads, frogs, lizards, and snakes, that habitually feed upon these insects. Azara says that almost all kinds of birds except the "milano" feed on them.[47]

The true ants are enemies of the white ants worthy of especial mention. The abundance of the ants and their pugnacious dispositions make them serious obstacles to the development of the termites' colonies, and they are probably their worst natural enemies. The termites have in their colonies forms that are known among biologists as soldiers, but so far as I have been able to determine from personal observations these soldiers do not attack the true ants, though they do take the place of sol-

[43] A. R. Wallace: The geographical distribution of animals, vol. ii, p. 247. New York, 1876.

[44] Alfred R. Wallace: The geographical distribution of animals, vol. i, pp. 245-246. New York, 1876.

[45] The flesh of the *tatus* is very much prized for food, and this naturally leads to the hunting and killing of these animals, which should be protected.

[46] George Gardner: Travels in the interior of Brazil, p. 280. London, 1846.

[47] Don Felix de Azara: Voyages dans l'Amérique Meridionale, vol. i, p. 192. Paris, 1809.

diers in obstructing the passage of the ants into the termites' nests and galleries.

The result of the relations existing between the true ants and the termites is that the two kinds do not thrive together; at least I have never found the termites' nests where the *saúbas* or other true ants were notably abundant. Preyed on by the true ants and by animals of so many different kinds, and even by insects themselves, it occurs to one that their chances of survival in the midst of so many enemies must be very small. That survival appears to be due largely to their habit of living and working under the protection of their covered roadways, and to the fact that their roads are constructed of materials that are remarkably inconspicuous. Nothing could look more thoroughly abandoned and lifeless than the common run of white ants' nests and their covered passages; yet if one breaks through these coverings he will usually find them fairly swarming with life.

My general impression is that those white ants which build mounds of earth are especially abundant in the highlands of Minas Geraes and through the semi-arid portions of Sergipe, Bahia, Goyaz, Matto Grosso, and the interior of Ceará, Maranhão, and Piauhy. Mr. Crandall tells me that he finds them most common on the Diamantina plateau. (Letter of June 23, 1909.)

STRUCTURES ABOVE GROUND

General characteristics.—The nests of the white ants, or *cupim*, have no visible external openings. When a mound is new or is being added to, the outside of the new portion is so soft that it can be readily broken off with a stick; but with time the outside usually becomes as hard as a brick. This hard outside covers the entire mound, and is usually about 6 inches thick, but in the very big nests it is sometimes nearly or quite a foot thick. Inside of this hard, thick covering the materials are quite soft and brittle, and the partitions are sometimes almost as thin as paper, though thicker in the larger nests. Where the mound stands on the ground, the cavities of the upper portion connect through the perforated base with subterranean excavations.

Parts of the nests are made of the excrement of the inhabitants. I have often broken the nests or the covered roads of these insects in order to observe the workers repair them. In every case observed the repairs were made by building up a wall or covering of excrement or something of the kind. At least it is voided from the posterior part of the body in a plastic condition, and is smoothed down on the sides so that the later layers always override the earlier ones on both sides of the wall. An ex-

amination of their construction, however, shows that they are made partly of clay or the earth about the nest and partly of woody fiber. These two substances are variously mixed in structure, sometimes one being more abundant, sometimes the other. An examination of the

FIGURE 5.—*Above-ground Structure of White Ants*

Seven kilometers west of Queluz, between Piquiry and S. Gonçales, State of Minas Geraes. From a photograph by the author, August 4, 1907

materials of the outside part of the large and old nests, however, shows that this part of the nest at least contains fragments of quartz, sand grains, and such like rock fragments that could not possibly have passed

through the bodies of the insects. The structure of some of the nest walls suggests that these walls are constructed partly of earth and rock fragments brought up from beneath the ground and built into the nests

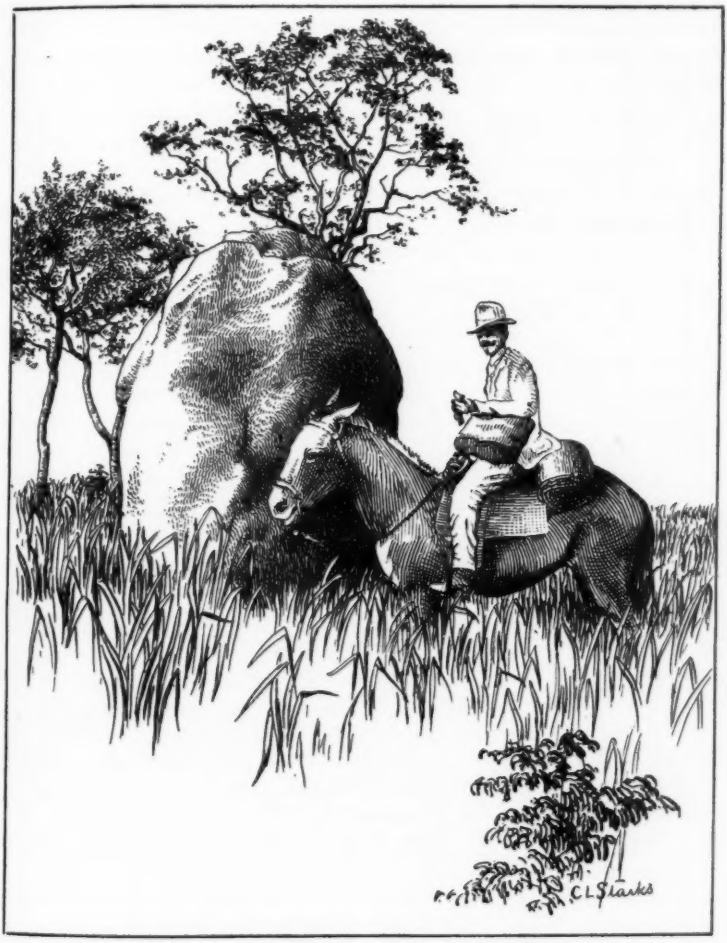

FIGURE 6.—*Mound of Termites or White Ants, State of Minas Geraes, Brazil*
From a photograph by R. Crandall, July, 1909

by cementing them together with excrement or some other adhesive substance.

The outer parts of the nests, when they stand on the ground, are, so far as my observations go, always made of earth cemented in a thick, hard wall. In the inner portions of the nest the partitions are thinner, and though they are made largely of an easy-spreading clay, they are often made partly, or at least overspread, with a dark, friable substance that has the appearance of being masticated wood, leaves, or other organic matter.

The openings through the mass of the nests are pretty uniform in size, being from 3 to 10 millimeters in diameter and averaging close to 5 or 6 millimeters. The openings within the nests sometimes have the appearance of being arranged in rude tiers; sometimes they are apparently haphazard labyrinths.

The external forms of the nests vary considerably, but unfortunately I do not know whether this variation is due to difference in the species of termites, to difference in the nature of the ground, or to other causes.

As a rule the mounds are rudely domed, rounded or conical, and the method of adding to the outside gives them a bumpy, lumpy appearance, so that, as Burmeister suggests, they resemble gigantic Irish potatoes. In some localities they are mostly tall and slender. Most of the tall, slender forms observed have been in wet ground or on ground that is sometimes overflowed. For this reason it is inferred that these forms are due to the presence of water rather than to a different species of termites. In size they also vary greatly. I have seen them as much as 6 meters high and 8 meters in circumference, but these very large ones are exceptional.

In southern Minas, south of Barbacena, Dr. R. Walsh notes mounds of the white ants 10 or 12 feet high: "I rode close by several which were considerably higher than my head on horseback and 9 or 10 feet in circumference."[48]

Charles J. Dulley tells me that in the vicinity of Caximbu, in southern Minas, he has seen white ants' nests 4 meters high and nearly 2 meters in diameter at the base. Mr. H. E. Williams, assistant on the Geological Survey of Brazil, says that in the vicinity of Taubaté, in São Paulo, they are often 2.4 meters high, while about the city of São Paulo they usually are 1 meter and less in height.

Gardner says that many of the level tablelands of the interior of Piauhy, where the soil is red clay, the mounds of white ants are abundant and often 6 or 8 feet high.[49]

[48] Rev. R. Walsh: Notices of Brazil in 1828 and 1829, vol. ii, p. 50. Boston, 1831.
[49] George Gardner: Travels in the interior of Brazil, p. 280. London, 1846.

In the valley of Rio Sapão, in northwest Bahia, Wells notes great numbers of white ants' nests from 4 to 6 feet high.[50]

At and about Asuncion, in Paraguay, I found the nests very abundant on the clayey soils, and many of them as much as 3 meters high.

The outer portion of the nest being thick, hard, and compact, and the inside being friable and easily removed, it is a custom in the interior of Brazil and Paraguay to scoop out the inside of white ants' nests and to use them for ovens. The door is cut near the base of the cone, and the inside parts removed through it.

The accompanying illustrations will probably give a better idea of the sizes and shapes of the nests than verbal descriptions.

FIGURE 7.—*White Ants' Nest, built of Earth, in the State of Minas Geraes*
From a photograph by R. Crandall, July, 1909

I add short extracts concerning these nests taken from other writers. The following is translated from Auguste de Saint-Hilaire:[51]

"In the vicinity of Parahyba we saw along the side of the road the nests of the termites, or white ants; further on we saw nothing of them, but near Pinho Velho, and especially near the Mantiqueira, we found large numbers of them. . . . The nests of the species common to the vicinity of Mantiqueira are made of a much masticated clayey earth. They are nearly cylindrical,

[50] J. W. Wells: He says that in that part of Brazil the mounds are often occupied by bees. Three thousand miles through Brazil, vol. ii, p. 127. London, 1886.

[51] Voyage dans les provinces de Rio de Janeiro et de Minas Geraes, vol. i, p. 108. Paris, 1830.

rounded at the top, and look like mile stones. Most of them are two or three feet high, but some of them are as much as five or six feet high, and I saw one that must have been twenty feet high and about as big round the middle where it was enlarged. The outside is covered with a crust as thick as a finger length, and no openings appear in it. The insides of some of these nests that have been overturned showed a series of black horizontal floors (planchers), one above another, close together, and pierced by round holes.

"The termites do not build their nests all at once. They enlarge them in proportion as the population of a colony increases, and the new parts are readily distinguished by the earth freshly laid on."

Sir Woodbine Parish speaks of "Corrientes and Paraguay, where whole plains are covered with their dome-like and conical edifices, rising 5 and 6 feet and more in height."[52]

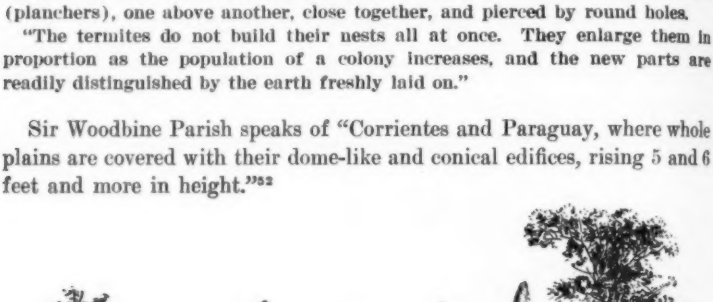

FIGURE 8.—*White Ants' Nest of Earth in Matto Grosso, on the Plains of the Upper Paraguay*

Sketch by J. C. Branner

In the region about the headwaters of the Paraguay the nests of the white ants are extremely abundant in favorable localities, and the forms of the nests are different from those noted in other parts of tropical America. The tall and very slender forms are especially noticeable in the low, flat prairie lands south of Cuiaba. (See figure 8.) These slender forms are known in that part of Brazil by the Indian name of *tacurú*.

Dr. João Severiano da Fonseca has the following in regard to ants in the vicinity of the city of Matto Grosso:[53]

[52] Sir Woodbine Parish: Buenos Ayres and the provinces of the Rio de la Plata, 2d ed., p. 252. London, 1852.

[53] Viagem ao redor do Brazil, vol. I, p. 352. Rio, 1881.

"The ants and the various kinds of *cupim* own the country. It is noteworthy that while their hives, or houses, vary in form according to the locality, they retain a certain uniformity of construction, having one shape here, another one there, and a different one somewhere else. I am unable to determine whether these differences depend on the soil and the materials of which they are constructed or upon the difference in the species of the constructors. It is certain, though, that in the vicinity of Cambara the country is covered with cylindrical columns called *tacurús* by the Indians. These are sometimes two metres high, and resemble the marks or columns known as stone friars. In some places, as below Corixa, on the Lixal and Burgres plateaus, they look like miniature castles half a metre high, with loopholes, gates, towers, and terraces. In other localities, such as Palma Real and Petas, they are lower, but thicker, sometimes isolated, and sometimes built against trees, but always very hard and made with a kind of bituminous cement that is impermeable to water."

Dr. Henry Drummond has the following on the white ants in tropical Africa:[54]

"The material excavated from these underground galleries and from the succession of domed chambers—used as nurseries or granaries—to which they lead, has to be thrown out upon the surface. And it is from these materials that the huge ant-hills are reared which form so distinctive a feature of the African landscape. These heaps and mounds are so conspicuous that they may be seen for miles, and so numerous are they and so useful as cover to the sportsman that without them in certain districts hunting would be impossible. The first things, indeed, to strike the traveller in entering the interior are the mounds of the white ant, now dotting the plain in groups like a small cemetery, now rising into mounds, singly or in clusters, each thirty or forty feet in diameter and ten or fifteen in height; or, again, standing out against the sky like obelisks, their bare sides carved and fluted into all sorts of fantastic shapes (see figure 9). In India these ant-heaps seldom attain a height of more than a couple of feet, but in Central Africa they form veritable hills, and contain many tons of earth. The brick houses of the Scotch mission station at Lake Nyassa have all been built out of a single ants' nest, and the quarry from which the material has been derived forms a pit beside the settlement some dozen feet in depth. A supply of bricks as large again could probably still be taken from this convenient depot, and the missionaries on Lake Tanganyika and onwards to Victoria Nyanza have been similarly indebted to the labors of the termites. In South Africa the Zulus and Kaffirs pave all their huts with white-ant earth, and during the Boer war our troops in Prætoria, by scooping out the interior from the smaller beehive-shaped ant-heaps and covering the top with clay, constantly used them as ovens. These ant-heaps may be said to abound over the whole interior of Africa, and there are several distinct species. The most peculiar as well as the most ornate is a small variety from one to two feet in height, which occurs in myriads along the shores of Lake Tanganyika. It is built in symmetrical tiers, and resembles a pile of small rounded hats, one above another, the rims depending like

[54] Henry Drummond: Tropical Africa, pp. 89-90. New York, 1891.

eaves, and sheltering the body of the hill from rain. To estimate the amount of earth per acre raised from the water-line of the subsoil by white ants

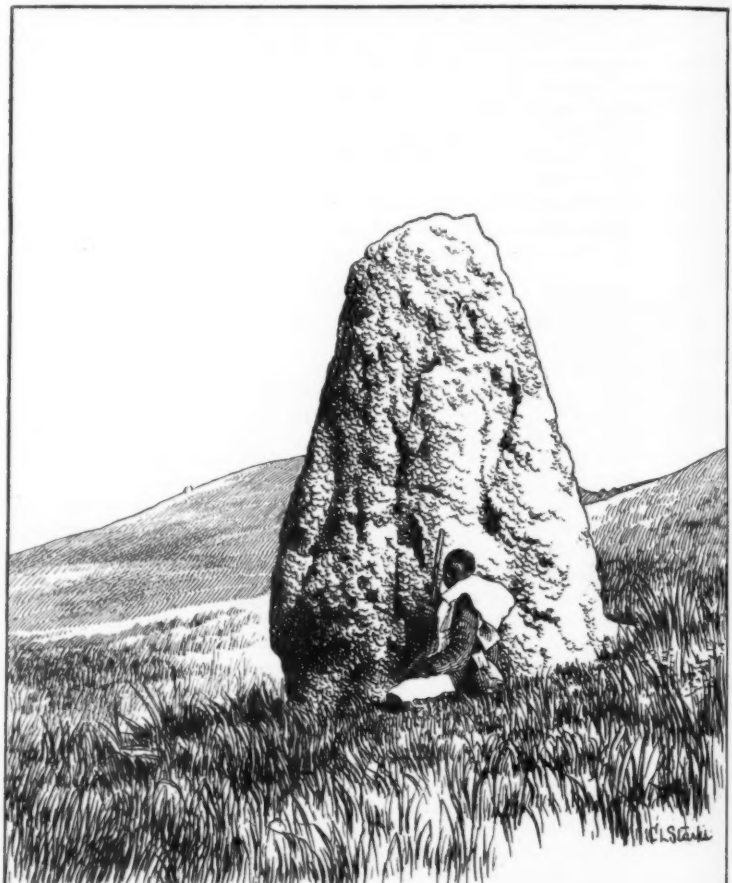

FIGURE 9.—*Mound of White Ants in the laterite Region of Africa*

Redrawn from "Il Ruwenzori," parte scientifica, volume ii. Prof. Alessandro Roccati. Petrografia e mineralogia. Milano, 1909, plate I. figure 1

would not in some districts be an impossible task, and it would be found, probably, that the quantity at least equalled that manipulated annually in temperate regions by the earth-worm.

"These mounds, however, are more than mere waste-heaps. Like the corre-

sponding region underground, they are built into a meshwork of tunnels, galleries, and chambers, where the social interests of the community are attended to."

Age of the mounds.—The method of building the mounds and the habits of the termites, so far as I am acquainted with them, lead to the conclusion that the size of a mound is determined by its age and by the size of the colony building it. Just how long it requires to build the large mounds I have but little means of judging. One frequently sees nests built on houses and fences, and in these cases it has been possible to determine the maximum ages of these particular nests. These cases, however, afford only a suggestion. The oldest nests I have seen, and of which I could get an idea of their ages, were not more than 50 years old, and the biggest of them contained a little less than 1 cubic meter of earth, the estimate being made without reference to the cavities within the mass.

It is evident that the size and age in one of these cases may or may not help one to determine the time occupied in the construction of one of the very large nests figured in this paper, for the rates of building may have been very different.

UNDERGROUND STRUCTURES

The above-ground structures of the white ants connect with underground passageways, but wherever I have seen these passageways opened they appear to have been excavated and then to have been filled with smaller chambers made of materials like that used to make the chambers of the mounds above ground. An examination of the thin chamber walls found in some of the underground excavations shows that they have been constructed of soft, plastic materials so piled up that each later addition overlaps the preceding one on both sides of the wall. The materials are partly of reddish clay like that of the ground in which the nest is made, and partly of a dark brown substance that I take to be organic matter—probably masticated plants.

I have never seen the excavations made by the white ants more than a meter and a half below the surface, but I have heard of them being found considerably deeper. My friend, Dr. Joaquim Lustosa, of Lafayette, State of Minas Geraes, writes me on this subject: "As for the depth to which they penetrate the ground, it is my impression that it is but little more than 3 metres."

RELATION OF NESTS TO THE SOIL

The white ants do not seem to be so dependent on the character of the soil as do the true ants. This is probably due to the fact that when the

true ants excavate their tunnels in the earth they depend on the character of the ground and the form of the excavations to support the structures. The white ants, on the other hand, depend partly on the nature of the soil, but partly on their method of cementing the materials of which their nests are made.

The preference, however, of the termites for certain soils and certain localities is very evident in some districts. On the upper Paraguay places have been seen where the nests are quite thick over certain areas, while there were none, or but few, on an adjoining area. Wherever these marked contrasts have been observed, however, they have apparently been due to a difference in the amount of moisture in the ground. I have thought that the white ants are sometimes found in rather wet ground, because they are there comparatively free from the attacks of their enemies, the true ants.

Opinions of Brazilians in regard to the distribution of the termites' nests vary considerably; some think they are more abundant in the open campo regions than in the forests; others think they prefer fields; still others think they are favored by a dry climate. All of these views appear to have more or less support. I have much doubt, however, about the theory of their preferences for campos. It is true that they do appear very abundant in the campo regions, but I am of the opinion that the apparent abundance is deceptive and due to the fact that all the nests are visible at once over a wide area (see plate 35, figure 2), while in a forest-covered area no nests, or but few nests, can be seen on account of their being concealed by the dense vegetation. This impression has been deepened by the fact that in several instances where the forests have been cleared away the mounds of the white ants appear to be quite as abundant as they are in the old clearings or on the open campos.

Further support is given this theory by Maximilien, Prince de Wied-Neuwied, who, in speaking of the white ants' nests near Conquista, in the southwestern part of the State of Bahia, says that they are extremely abundant in covered and wooded places.[55]

RELATIONS TO VEGETATION

Compared with the true ants, the white ants are harmless. At least they do not attack crops and animals or render certain localities uninhabitable. The harm they do to agriculture is confined to the mere encumbrance of the ground by their big, hard, rock-like nests. They do, however, destroy wood used in the construction of fences, houses, bridges,

[55] Voyage au Brésil, vol. III, p. 120. Paris, 1822.

and furniture, and they sometimes burrow into books and papers that are left to stand for a long time undisturbed.

I quote below some remarks of other writers in regard to the destruction of timbers by termites, but I must add that I am disposed to question the rate at which these insects are said to destroy wood. My own observations lead me to conclude that the idea expressed by Drummond and others that a piece of furniture may be destroyed in a night is simply a picturesque way of putting it. In the first place, there are certain kinds of wood (in Brazil at least) that the termites do not attack at all. I am unable to say just now what kinds they are, but it is a matter of common information among Brazilian carpenters and cabinet-makers.

In the second place, the method of discovery of their destructive work frequently leaves an erroneous impression. In accordance with their general habit of keeping away from the light, termites attack a piece of wood that forms a part of a building from within. Their work does not appear at the surface at all, and it may be carried on for months, or even for years, without its being discovered. But some day a window-sill crushes in, a door-post is shattered by a trifling blow, or a rafter gives way without its ever having been suspected that they were being attacked by the cupim. The suddenness of the discovery not unnaturally leads to the unwarranted inference that all this work was done during the preceding night.

The following quotation is taken from pages 78-83 of Dr. Henry Drummond's little book called "Tropical Africa," was has an interesting chapter on white ants (pages 77-94):

"The termite lives almost exclusively upon wood, and the moment a tree is cut or a log sawn for any economical purpose this insect is upon its track. One may never see the insect, possibly, in the flesh, for it lives underground, but its ravages confront one at every turn. You build your house, perhaps, and for a few months fancy you have pitched upon the one solitary site in the country where there are no white ants. But one day suddenly the door-post totters and lintel and rafters come down together with a crash. You look at a section of the wrecked timbers, and discover that the whole inside is eaten clean away. The apparently solid logs of which the rest of the house is built are now mere cylinders of bark, and through the thickest of them you could push your little finger. Furniture, tables, chairs, chests of drawers, everything made of wood, is inevitably attacked, and in a single night a strong trunk is often riddled through and through and turned into matchwood. There is no limit, in fact, to the depredation by these insects, and they will eat books, or leather, or cloth, or anything, and in many parts of Africa, I believe, if a man lay down to sleep with a wooden leg it would be a heap of sawdust in the morning. So much feared is this insect now that no one in certain parts of India and Africa ever attempts to travel with such a thing as a

FIGURE 10.—*Nests of White Ants in Africa*
From "Tropical Africa," by Henry Drummond, opposite page 88

wooden trunk. On the Tanganyika plateau I have camped on ground which was as hard as adamant, and as innocent of white ants, apparently, as the pavement of St. Paul's, and awakened next morning to find a stout wooden box almost gnawed to pieces. Leather portmanteaus share the same fate, and the only substances which seem to defy the marauders are iron and tin."

The following extracts give an idea of how the work of the white ants looks from the point of view of the civil engineer:[56]

"The forests contain some varieties of hardwoods which would be suitable for permanent structures were it not for the ravages of insects. A species of white ant, called locally 'cupim,' appears to be the most destructive. These insects seem to attack timber bridges more than they do the timber ties, which are partially buried in the ground. They work in armies, building nests and artificial tunnels on the outside of bridge timbers and working into the heart of the timber from the ends. Although the largest of the 'cupims' yet observed is no longer than ¼ inch, so rapid and destructive is their action that the life of a timber bridge can hardly be considered more than two years. Frequently stringers and timbers whose ends butt together, appearing perfectly sound on the outside, are found in an incredibly short time to be so thoroughly honeycombed by this energetic little creature as to become unsafe members in a bridge or other important structure. No satisfactory method of preventing the action of the 'cupims' has yet been found here. Kerosene poured over a nest or into a tunnel will kill the insects within. The timber can then be scraped clean, but another army is soon at work again.

"Timber bridges have been built at various places to expedite the work and get the rail head to the front, but for permanency steel and masonry are the only materials suitable. A considerable quantity of pine lumber from the Southern States is being used for building purposes in Porto Velho. The experience up to date indicates that the insects do not attack this resinous wood, but not sufficient time has yet elapsed to prove conclusively that pine lumber will withstand their ravages. Ties of native lumber used in the track, either on account of the vibrations of passing trains or the partial covering of earth, resist the 'cupim' more successfully."

It should be noted that although the white ants are abundant in forests, I am not aware that they ever attack the living trees. They appear to eat only the dead trunks or dead limbs or bark. Many of them build their nests on the trees. Nests found high up on tree trunks are always, so far as I have observed, made of woody matter and not of earth. Those on trunks, only a meter or two above the ground, are often made partly of woody matter and partly of earth.

PHOSPHORESCENCE

It has been stated that some of the termites are luminous. On this subject see notes by Frederick Knab, *Science*, vol. xxx, October 22, 1909,

[56] John Y. Bayliss: The Madeira-Mamoré Railway. Engineering News, vol. lxii, p. 454. New York, October 28, 1909.

From "Tropical Africa," by Henry Drummond, opposite page 88

pages 574-575, and by J. C. Branner, *Science*, January 7, 1910, pages 24-25.

Herbert H. Smith, a thoroughly trustworthy entomologist, mentions phosphorescent termites near Santarem, on the lower Tapajos:

"There are white ant-hills along the sides (of the road)—pale glows of phosphorescent light, like coals in the ashes. . . . The phosphorescence is in the hills themselves, not, so far as I know, in the insects, and I believe that it is peculiar to the mounds of one or two forest species."[57]

FIGURE 11.—*White Ants' Nest in a Tree, Salitre Valley, State of Bahia*
J. C. Branner, 1907

Prof. Harold Heath, who has studied the termites of California, has given me the following statement:[58]

"Regarding the luminosity of termites, I can confidently assert that the three species (*Termopsis angusticollis*, *Calotermes castaneus*, and *Termes lucifugus*) living in the vicinity of San Francisco do not exhibit this peculiarity. The logs inhabited by these animals are occasionally infected by a species of phosphorescent slime mould (myxomycete), and when such colonies are disturbed at night, in the building of camp fires, for example, particles of brightly shining wood, or of the mould itself, may be seen attached to some of the individuals, but there is no true phosphorescence of the body. Furthermore, I have kept, during a period of several years, hundreds of colonies in glass jars placed in a cellar room, and these never showed any signs of the phenomenon in question."

[57] Herbert H. Smith: Brazil, the Amazon, and the Coast, p. 139. New York, 1879.
[58] Stanford University, California, February 7, 1910.

Geologic Work

EARTH MOVED

The amount of earth brought to the surface by ants in a few instances has been given. The calculations at page 469 show that in one case the earth brought up would cover the ground to a depth of 22.25 contimeters. The estimate of Gounelle, mentioned at page 470, makes the earth brought up 15 centimeters thick. In neither of these cases is it known how long the building of the mounds occupied.

Mr. Darwin's study showed that the earthworms in many parts of England bring to the surface annually 10,516 kilograms of earth to the acre.[59] In order to compare the work of ants with that of earthworms, it would be necessary to know how long the ant-hills were in process of formation. Unfortunately I have no trustworthy means of determining the ages of the mounds. If we assume an average of 100 years for the age of the mounds over the area measured (an average which seems to me quite conservative in this case), the total work of worms and ants would compare as follows:

Total weight of earth brought to the surface in 100 years over 1 hectare (10,000 square meters):

By worms in England	2,598,500 kilograms
By ants in Brazil	3,226,250 kilograms

It is to be noted that the amount of work done in both instances is rather exceptional—that is, localities were selected favorable for exhibiting the activities of worms in one case and of ants in the other.

I have no trustworthy data showing the amount of earth brought to the surface by termites over a definite area. The places seen where the nests were most abundant were in low, inaccessible grounds on the upper Paraguay. My impression is that in those particular localities there was less earth brought up than in the case of the true ants cited above.

The sizes of individual white ants' nests were frequently measured. One of the largest I ever saw in Minas Geraes was 6 meters high and 8 meters in circumference 2 meters above the ground, and contained 30.55 cubic meters of earth, no account being taken of the porous nature of the structure, which would probably reduce this total by 3 or 4 cubic meters.

Another unusually large mound in the State of Minas was 4 meters high and 7 meters in circumference 2 meters above the base, and contained 15.59 cubic meters of earth. These are individual cases, however,

[59] Charles Darwin: The formation of vegetable mould through the action of worms, p. 305. New York, 1882.

and I am unable to say how large an area the contents can properly be distributed over, how long the termites were in doing the work, or how large the colonies were that made them.

In the case of the white ants, the earth undergoes some process of digestion and passes through the bodies of these insects, so that the chemical effect is probably more important than the mere upturning it gets from the true ants.

ORGANIC MATTER

The true ants carry into their burrows enormous quantities of leaves and other organic matter. These leaves must yield either directly or indirectly organic acids, which help attack the soil, the minerals, and the rocks with which they come in contact.

The organic matter carried into their burrows by the termites consists chiefly of the decayed wood and other vegetation eaten by them. These materials, however, can not fail to contribute organic acids that help attack the minerals of the soil and adjacent rocks.

OPENINGS IN THE SOIL

The extensive subterranean excavations, especially those of the true ants, permit the freer circulation of atmospheric air and of carbon dioxide. These channels must also serve from time to time for the passage of meteoric waters, and their great extent and ramification must hasten very considerably all the processes of atmospheric disintegration and alteration of soils, minerals, and rocks.

Unfortunately we have no observations at present that enable us to give quantitative values to these underground agencies and activities. We only know that the openings beneath the surface are rudely equal to the amount of soil in the above-ground structures.

RÉSUMÉ

Ants and termites are vastly more numerous in tropical America than they are in the temperate regions.

They show a marked preference for, or rather their structures stand up better on, clayey than on sandy soil.

They affect the geology, especially the soil and subsoil, both directly and indirectly.

Directly:

1. By their habits of making underground excavations that radiate from a central nucleus and often aggregate several miles in length.

2. By opening the soil to atmospheric air and gases.

3. By bringing to the surface large quantities of soil and subsoil.

4. By introducing into their subterranean excavations large quantities of organic matter which must yield acids that affect the soil and the subjacent rocks.

5. By using these excavations for habitations and the production of gases that attack the soil and its contained minerals.

Indirectly:

6. By the periodic passage and circulation of meteoric waters through their extensive tunnels.

7. By affecting the availability of the soil for agricultural purposes.

8. By affecting the habitability of the land by man.

9. By the destruction of crops.

10. By the consumption (by termites) of dead plants and of timbers and lumber used in houses and for the manufacture of furniture, machinery, etcetera.

Although the data available are defective, we seem to be warranted in concluding that ants and termites are quite as important geologic agents in tropical America as are the earthworms of temperate zones.

They are also factors of great importance from an agricultural, economic, and social point of view.

Postscript

Since this article was in type I have received the following letter from my Brazilian friend, Dr. Joaquim Lustosa, in regard to the subject of the luminosity of termites mentioned on pages 491-492. The letter is dated Lafayette, State of Minas Geraes, Brazil, July 8, 1910:

"I have just received authentic information to the effect that in the State of Matto Grosso, in the low, swampy lands along streams, and especially in the rainy months beginning with October, myriads of fireflies are seen covering the ground. My informant, who has lately come from the upper part of Matto

Grosso where it joins Bolivia, tells me that he has seen at night many of the nests of white ants that have been abandoned by the ants themselves entirely covered by fireflies that come from the small openings over the whole surface of the ant-hill. Is it possible that the fireflies select these abandoned ant-hills as places in which to grow their larvæ? . . . Unfortunately I have never observed anything of the kind hereabout, though I have been interested in the subject in order to furnish you information."

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INTERNAL CHARACTERS OF SOME MISSISSIPPIAN RHYNCHONELLIFORM SHELLS[1]

BY STUART WELLER

(Presented by title before the Society December 31, 1909)

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[1] Manuscript received by the Secretary of the Society April 29, 1910.

Introduction

Among all the Paleozoic brachiopods no type of shell configuration has greater range, greater distribution, or greater representation than the rhynchonelliform shells, and previous to the appearance of the great work on the Genera of Paleozoic Brachiopoda, by Hall and Clarke,[2] the more common custom was to refer all these shells to the genus *Rhynchonella*. It was pointed out by these authors, however, that the genotype of *Rhynchonella, R. loxia* Fischer, from the Upper Jurassic fauna of Russia, was, in its assemblage of external and internal characters, clearly distinct, generically, from any of our Paleozoic forms. They recognized, furthermore, no less than sixteen generic or subgeneric groups of rhynchonelliform shells in the Paleozoic faunas, to which either new names were given or for which previously published names were revived. No attempt was made by these authors to distribute all the species of Paleozoic Rhynchonelloids in their proper genera, but in his "Synopsis of American Fossil Brachiopoda" Schuchert[3] has attempted to so distribute the species so far as was possible. More than a hundred species, however, were allowed by Schuchert to remain in the genus *Rhynchonella*, because their internal characters had never been investigated and it was impossible to place them properly without such an investigation.

The present study is an attempt to determine the essential generic characters of some of the rhynchonelliform shells of the Mississippian faunas of the Mississippi Valley basin. The method of study has been to grind down the shells from the beak toward the front, on a carborundum wheel, the surface being polished and careful cross-section drawings being made at frequent intervals. From the drawings of these serial sections the internal arrangement of the septa and other lamelliform plates, the hinge-plate, crura, spondylia, and cruralia can be interpreted with ease. The investigation has been extended to include certain rhynchonelliform shells which have been referred to the Pentamerid genus *Camarophoria* by Hall and Clarke and by Schuchert, all of which were originally described as members of the genus *Rhynchonella*.

Camarophoria King[4]

Camarophoria schlotheimi (von Buch)

At the outset of the investigation it is important to determine the essential differences between *Rhynchonella*, used in its broad sense, and

[2] Paleontology of New York, vol. viii, parts 1 and 2 (1891-1894).
[3] Bulletin of the U. S. Geological Survey, No. 87 (1897).
[4] Superfamily Pentameracea Schuchert.

Camarophoria. Hall and Clarke have referred all those rhynchonelliform shells possessing a median septum in each valve, a ventral spondylium, and a dorsal cruralium to *Camarophoria,* and their diagnosis of that genus is clearly made, at least in part, from such rhynchonelliform shells as *R. subcuneata* and *R. subtrigona,* which are illustrated by them as typical of the genus. For the present study the essential characters of the genus *Camarophoria* have been determined by grinding specimens of *C. schlotheimi* from the Permian of Germany. Drawings of a series of eleven cross-sections of this shell are here persented in figure 1. The most diagnostic characters of the genus are found in the brachial valve where the hinge-plate is undivided and is supported by a strong median septum. From the lateral faces of the median septum a pair of horizontal processes arise close to the posterior extremity of the shell (figures 1*c, d, e*), which at first slope broadly and then curve more narrowly

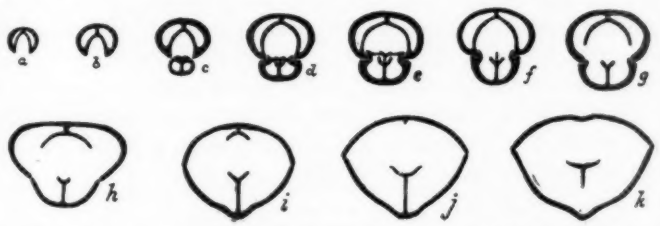

FIGURE 1.—*Cross-sections of the rostral Portion of Camarophoria schlotheimi (von Buch)*

This series of eleven cross-sections (× 2½) is from a specimen from the Permian of Pössneck, Germany

toward the hinge-plate with which the distal portions of the processes are joined posteriorly. Before the articulation of the valves is passed, however, the distal margins of the processes become free from the hinge-plate (figure 1*e*), and they constitute the two sides of a concave cruralium supported by a median septum from the floor of the valve, and in turn bearing a continuation of this septum along the middle line of its concave side which supports the undivided hinge-plate. The hinge-plate terminates abruptly in front, and is doubtless continued anteriorly in the crura, although these processes were not preserved in any of the examples sectioned. The cruralium continues anteriorly beyond the termination of the hinge-plate, and for a short distance the continuation of the median septum upon the concave side of the cruralium persists (figure 1*f*), although it becomes rapidly reduced and soon disappears. The cruralium continues with increasing elevation from the floor of the valve and in-

creasing width to near the middle of the shell, and is even extended somewhat beyond the anterior limit of the median septum upon the floor of the valve.

In the pedicle valve the hinge-teeth are supported by strong dental lamellæ which are joined to form a broad spondylium supported by a median septum from the floor of the valve. Beyond the articulation of the valves the inner margins of the lamellæ become free. The spondylium is much broader and deeper than the cruralium of the opposite valve and is attached to the floor of the valve by a much lower median septum; it rapidly becomes shallower and narrower anteriorly, terminating before the cruralium of the brachial valve has reached its maximum expansion. The median septum continues a short distance beyond the extremity of the spondylium, but quickly disappears. Hall and Clarke[5] mention "two accessory supporting lamellæ abutting on one side against the outer surface of the converging dental plates, and on the other against the interior cardinal surface of the valve," but these have not been observed in any of the specimens sectioned, although they are present in at least two of the species referred to the genus *Camarophoria* by the same authors, *C. subcuneata* and *C. subtrigona*, neither of which species possess the true cruralium of the brachial valve which is so conspicuously developed in *C. schlotheimi*.

CAMAROPHORIA HAMBURGENSIS N. SP.

Among the Mississippian species which have been investigated, only two possess the essential characters of *Camarophoria* as exhibited by the genotype, and neither of these were referred to the genus by Hall and Clarke. The first is an undescribed species which may be designated as *C. hamburgensis*. It occurs commonly in the thin Hamburg oolite bed near the base of the Kinderhook at Hamburg, Calhoun County, Illinois.[6] The species occurs for the most part as detached valves, and a series of sections of both the pedicle and brachial valves is shown in figure 2. In the brachial valve this species is essentially like *C. schlotheimi* except that the lateral processes of the median septum, which are produced into the cruralium, arise nearer the floor of the valve, and their distal margins do not curve up sufficiently to become attached to the under surface of the hinge-plate, but always remain free (figures 2*k*, *l*). As in *C. schlotheimi* the median septum appears to pass through the cruralium in the apical portion of the valve as a support to the hinge-plate, and after it has ceased to render this support it is continued as a gradually disappearing

[5] Paleontology of New York, vol. viii, part 2, p. 213.
[6] Transactions of the Academy of Science of Saint Louis, vol. xvi, p. 465.

median ridge along the concave side of the cruralium (figures 2*m*, *n*, *o*), the cruralium itself gradually increases in elevation and in width, finally becoming narrower and terminating abruptly. In the pedicle valve the

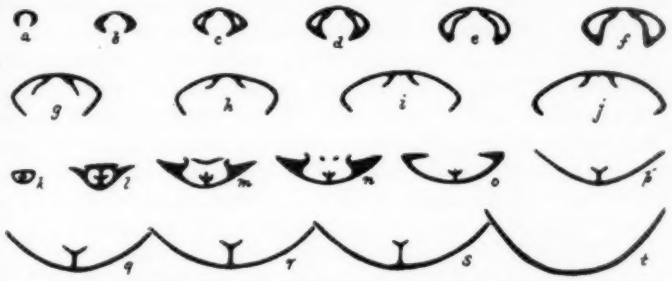

FIGURE 2.—*Cross-sections of the rostral Portion of the Pedicle Valve, and a Like Series of the Brachial Valve, of Camarophoria hamburgensis n. sp.*

This series of ten cross-sections (× 2½) is from specimens from the Kinderhook oolite at Hamburg, Calhoun County, Illinois

dental lamellæ are not joined to form a true spondylium, supported by a median septum from the floor of the valve, but they do form a spondylium-like process which rests directly upon the floor of the valve.

CAMAROPHORIA EXPLANATA (McCHESNEY)

A second species which is apparently a typical member of the genus *Camarophoria* is *C. explanata* (McChesney), which was referred to the genus *Pugnax* by Hall and Clarke. Externally this species closely resembles certain rhynchonelliform shells which have commonly been referred to *Pugnax*. The example illustrated by Hall and Clarke was a very perfect sulphur cast of McChesney's type specimen, which of course gave no indication of median septa in either valve and was naturally referred to *Pugnax*, but these characters were observed by Schuchert, who correctly referred it to *Camarophoria*.[7] In figure 3 a carefully prepared series of sections of this species is shown. The lateral processes from the sides of the median septum of the brachial valve are short and are situated high above the floor of the valve (figures 3*c*, *d*, *e*). In the section nearest the apex of the brachial valve these cruralium processes are apparently consolidated with the beginning of the hinge-plate (figure 3*b*), but the separation is complete from its origin, the distal margins of the processes not being joined to the under side of the hinge-plate for a short distance, as in *C. schlotheimi*. The median septum rising from the concave floor

[7] Bull. of the U. S. Geological Survey, No. 87, p. 162.

of the cruralium continues to the anterior margin of the hinge-plate, and even beyond, where it supports the bases of the crura (figure 3*f*), but beyond this point it is rapidly reduced and soon disappears. The cruralium is narrow, never attaining the width of that in the other two species which have been described, but becomes gradually wider toward the front; it becomes highly elevated above the floor of the valve anteriorly and is produced beyond the base of the median septum. The crura are strongly curved toward the opposite valve soon after the disappearance of the supporting median septum (figure 3*g*). In the pedicle valve the dental plates are curved toward the median line of the valve and form a spondylium which rests directly upon the floor of the valve posteriorly, but is supported by a low median septum anteriorly; it is not continued so far toward the front of the shell as is that of the brachial valve.

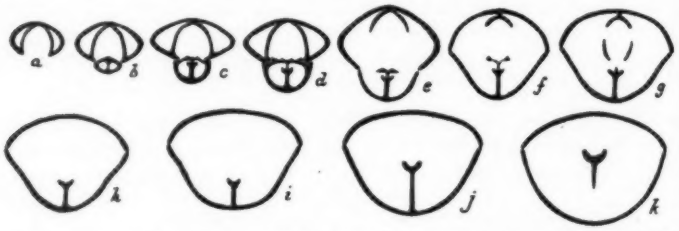

FIGURE 3.—*Cross-sections of the rostral Portion of Camarophoria explanata* (*McChes.*)
This series of eleven cross-sections (× 2½) is from a specimen from the Chester limestone of Illinois

The development of a true cruralium in the brachial valve is considered as the essential generic character of the three species just described. This cruralium is fundamentally different from the cruralium-like crural cavity between the lateral portions of the divided or undivided hinge-plate of many of the rhynchonelloid shells, which does not continue anteriorly beyond the hinge-plate and which does not support, along the median line of its concave surface, a continuation of the median septum. The criterion which has come to be used during late years for the placing of a rhynchonelliform shell in the genus *Camarophoria*—that is, the presence of a median septum in each valve—must give way to the character of the cruralium of the brachial valve. Many rhynchonelloid shells possess a distinct median septum in the brachial valve, and the fact that the dental lamellæ of the pedicle valve converge somewhat more rapidly in some examples and become joined as they reach the floor of the valve, or even before they reach it, and thus give rise to a median septum, is not sufficient basis for placing them in a different family, and even in a differ-

ent order, as has been done by some students of the brachiopods. The presence or absence of the pedicle median septum in the true Rhynchonelloids is dependent solely upon the modification of certain elements, the dental lamellæ, which are present in all of the shells. The cruralium of the brachial valve, on the other hand, as developed in the species of *Camarophoria*, is a totally distinct morphologic element in the structure of the shell, and its presence is well worthy of recognition as of more than generic importance.

TETRACAMERA N. GEN.[8]

TETRACAMERA SUBCUNEATA (HALL)

Among the rhynchonelliform shells possessing a pedicle median septum, and referred for the first time to the genus *Camarophoria* by Hall and Clarke, is *Rhynchonella subcuneata* Hall. A series of cross-sections

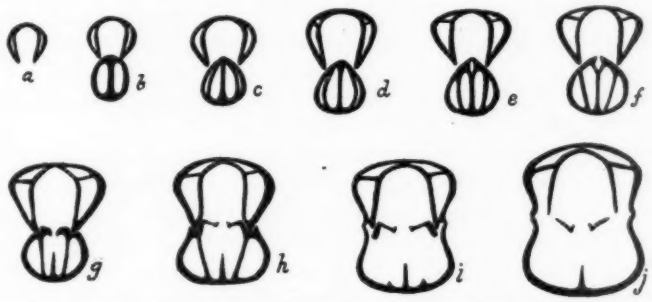

FIGURE 4.—*Cross-sections of the rostral Portion of Tetracamera subcuneata (Hall)*
This series of ten cross-sections (× 2½) is from a specimen from the Salem limestone of Indiana

of this common species of the Salem limestone is shown in figure 4. The median septum of the brachial valve is undivided at the apex of the valve (figures 4*b*, *c*, *d*), but before the articulation of the shell is reached a median incision is formed internally which is at first arched over (figure 4*e*), but soon becomes open on the cardinal side by the incision between the lateral divisions of the hinge-plate (figure 4*f*). This cruralium-like or crural cavity[9] is very short, not even extending anteriorly to the articulation of the valves, although the median septum continues with gradually decreasing height, sometimes to near the middle of the valve.

[8] Superfamily Rhynchonellacea Schuchert.

[9] This cavity is morphologically different from the cruralium of *Camarophoria*, and will hereafter be referred to as the *crural cavity*.

This structure is totally different from that of *Camarophoria,* in which a true cruralium is developed between the level of the hinge-plate and the floor of the valve, and continues as far anteriorly or even beyond the base of the median septum. The character of the median septum and crural cavity in this species is essentially identical with that of *Camarotœchia* and of several other undisputed rhynchonelloid genera. The species possesses, in addition to the median septum, two lateral lamellæ in the brachial valve which originate on the floor of the valve on either side of the base of the median septum and abut against the inner cardinal surface of the valve at their opposite extremity (figures 4*c, d, e, f, g, h*), these lamellæ, with the median septum, dividing the apical portion of the valve into four compartments. Anteriorly these lateral septa support the two lateral divisions of the hinge-plate directly opposite the hinge-sockets, to a point beyond where the inner margins of the divisions of the hinge-plate are supported by the divided median septum. These lateral lamellæ terminate abruptly, beyond the line of articulation of the hinge, and disappear entirely while the median septum is still considerably elevated.

In the pedicle valve the dental lamellæ are strongly developed and curve toward the median line as they approach the floor of the valve, forming a spondylium which rests directly upon the inner surface of the valve posteriorly, but which is raised upon a low median septum anteriorly. From the outer surface of each dental lamella a nearly horizontal plate passes across each lateral rostral cavity, joining with the inner surface of the outer shell wall. These lateral buttress plates have been observed in only one other rhynchonelloid shell, *R. subtrigona* M. & W., and they are the two accessory supporting lamellæ mentioned by Hall and Clarke in their diagnosis of *Camarophoria,* but which are wholly wanting, as has been shown, in the genotype of that genus, and are not known to be associated with the characteristic brachial cruralium of that genus. The peculiar association of characters in this species is believed to be sufficiently distinct from other rhynchonelloid shells to be worthy of recognition as a distinct and as yet undefined generic type, for which the name *Tetracamera* is herewith proposed. The genotype of this new genus is *T. subcuneata* (Hall), and the only other species which can as yet be included in it is *T. subtrigona* (M. & W.), which is next to be described.

TETRACAMERA SUBTRIGONA (M. & W.)

Tetracamera subtrigona is another rhynchonelliform shell which was placed in the genus *Camarophoria* by Hall and Clarke. This species is much larger than *T. subcuneata* and is proportionally much broader. Its

geologic horizon is the Keokuk limestone. The internal characters of the shell are exhibited in the series of cross-sections shown in figure 5. The rostral cavity of the brachial valve is divided by a median septum which is at first solid (figure 5*e*), but is soon excavated on the median line near the cardinal side of the valve. This median excavation is completely arched over to the line of articulation of the valves (figures 5*f*, *g*, *h*, *i*), beyond which it is open on the cardinal side by a narrow, median, slit-like incision (figures 5*j*, *k*, *l*), thus forming a crural cavity which differs from that of *T. subcuneata* in having a much greater anterior extension and in having the median incision on the cardinal side much narrower;

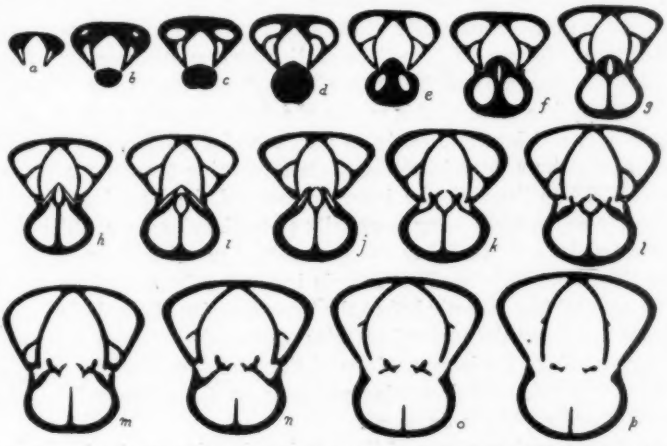

FIGURE 5.—*Cross-sections of the rostral Portion of Tetracamera subtrigona* (*M. & W.*)
This series of sixteen cross-sections (× 1¼) is from a specimen from the Keokuk limestone of Keokuk, Iowa

this structure, however, is totally different from that of the true cruralium of *Camarophoria*. At the line of articulation of the valves a shallow, broad, oblique cavity originates on each side of the central crural cavity (figures 5*h*, *i*, *j*), whose bounding wall on the cardinal side is much thinner than the inner wall. The inner walls may perhaps be compared with the two lateral septa of the rostral portion of the brachial valve of *T. subcuneata*, although their position is very different, their inner extremities abutting against the outer surface of the walls of the crural cavity and their outer extremity against the inner surface of the sides of the valve. Shortly after the origin of these lateral, oblique cavities, the crural cavity is differentiated into two portions (figure 5*i*) by the outgrowth from its inner surface of a pair of lateral processes which nearly

meet in the median line; the two portions of the cavity thus formed are of unequal size; the one toward the cardinal side is smaller, subcrescentic in form, and is completely arched over, as was the undivided cavity posteriorly. The arched covering of the smaller crescentic cavity quickly disappears and the slitlike, median, cardinal incision of the crural cavity opens freely toward the interior of the shell (figures 5*j*, *k*, *l*). The lateral, oblique cavities on each side of the central crural are inclosed upon the cardinal side but for a short distance (figures 5*k*, *i*, *j*), but the inner walls continue as supporting plates abutting against the outer surface of the walls of the crural cavity internally and against the inner surface of the lateral walls of the valve externally (figures 5*k*, *l*), and they continue beyond the anterior extremity of the crural cavity, giving support to the crural bases (figures 5*m*, *n*). The median septum continues well toward the anterior extremity of the valve with gradually decreasing height.

In the pedicle valve of this species the dental lamellæ unite to form a spondylium which rests directly on the floor of the valve, and each plate is supported by a lateral buttress plate connecting the outer surfaces of the dental lamellæ with the inner surfaces of the lateral walls of the valve, these structures being essentially as in *T. subcuneata*, although the buttress plates are situated nearer the cardinal margins of the valves, and they slope toward the cardinal margin in passing from the inner to their outer extremities. Shortly before the inner margins of the dental lamellæ become free from the cardinal margins of the valves these buttress plates cease to reach to the inner surfaces of the lateral walls of the valve, and continue as gradually decreasing processes on the outer surfaces of the dental lamellæ (figures 5*n*, *o*, *p*).

In the internal structure of its pedicle valve this species is essentially like *T. subcuneata*, and it is therefore placed with it in the genus *Tetracamera*, but the structure of the brachial valve is unique among all the species examined, and it is possible that these characters should be considered as of sufficient importance to justify the establishment of a distinct genus for the species.

RHYNCHOTETRA N. GEN.

RHYNCHOTETRA CAPUT-TESTUDINIS (WHITE)

Another rhynchonelliform shell referred to the genus *Camarophoria* by Hall and Clarke, apparently because of the presence of a median septum in each valve, is *Rhynchonella caput-testudinis* White. This species has a peculiar external configuration, differing markedly from all other rhynchonelliform shells of the Mississippian faunas in its elongate, trian-

gularly subovate form, its coarse plications, the great depth of the valves toward the beak, and the broad, concave lateral surfaces of the shell toward the beak. Material for the proper examination of the internal characters of a typical member of this species has not been available, but specimens of at least a closely allied form, which may perhaps be a distinct species, differing only in the arrangement of the coarse plications of the shell, have been investigated, and the series of cross-sections observed is shown in figure 6. In this shell the cross-section of the apical portion of the brachial valve is subtriangular in outline, and is divided by a median septum with a crural cavity internally, this cavity being arched over on its cardinal side (figure 6*a*). This condition persists to the be-

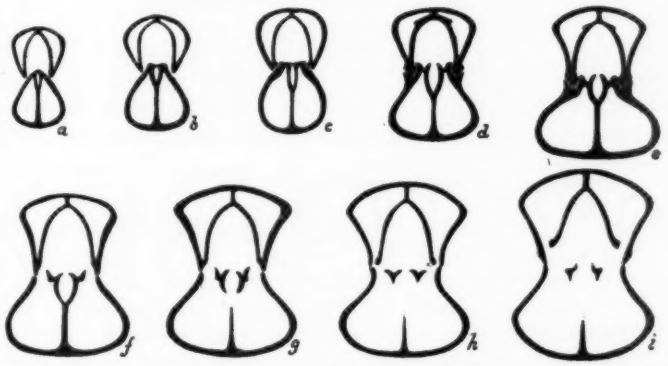

FIGURE 6.—*Cross-sections of the rostral Portion of Rhynchotetra caput-testudinis (White)* ?

This series of nine cross-sections (× 2½) is from a specimen from the Burlington limestone of Missouri

ginning of the articulation of the valves, with the cardinal surface becoming broader and flatter (figures 6*b, c*), but beyond this point the cardinal surface is open and the divided portion of the median septum forms an open crural cavity (figures 6*d, e*). The outer surfaces of the processes forming this cavity are at first connected laterally with the two portions of the divided hinge-plate, but anteriorly this connection with the lateral margins of the valves ceases (figure 6*f*), and shortly thereafter the connection with the median septum is broken (figure 6*g*), the lateral walls of the crural cavity passing into the bases of the crura. The median septum continues well toward the front with gradually diminishing height. In this valve there is no structure comparable with the cruralium as seen in the typical representatives of *Camarophoria*, the crural

cavity being identical in all essentials with the similar structure in many undisputed rhynchonelloid species.

In the pedicle valve the dental lamellæ are strongly developed and meet near the floor of the valve to form a spondylium which is supported by a median septum. Anteriorly the spondylium is progressively more elevated above the floor of the valve by the median septum. For a short distance, opposite the articulation of the valves, a pair of slight, lateral processes are present upon the outer surfaces of the dental lamellæ near their attachment to the median septum, which are possibly incipient lateral buttress plates such as are present in the genus *Tetracamera*.

Pugnax Hall and Clarke

PUGNAX PUGNUS (MARTIN)

The remaining species which will be considered here have never been removed from the family Rhynchonellidæ, although they have been distributed among several different genera, and in some cases their generic

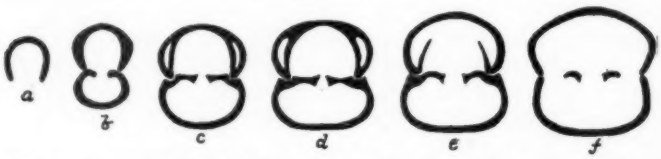

FIGURE 7.—*Cross-sections of the rostral Portion of Pugnax pugnus (Martin)*
This series of six cross-sections (× 2½) is from a specimen from the Mountain limestone of Ireland

reference has clearly been incorrect. Hall and Clarke have referred no less than five Mississippian species to the genus *Pugnax*, and Schuchert has placed the same species in the genus, the generic characters most commonly depended upon being the external configuration of the shell, most especially the obsolescence of the plications except toward the anterior margin of the shell. In order to have a standard for the comparison of the American species referred to this genus, one of the typical species of the genus, *Pugnax pugnus*, from the Mountain limestone fauna of Ireland, has been investigated, and the cross-sections secured are shown in figure 7. The structure of this shell is exceedingly simple. No median septum is present in either valve; the hinge-plate of the brachial valve is divided to the apex, and the dental lamellæ of the pedicle valve are short. None of the Mississippian species referred to the genus *Pugnax* by Hall and Clarke or by Schuchert possesses this simple structure, and in fact no species possessing the combination of this arrangement of

internal characters, with its peculiar external configuration, have been observed among those studied, and only two of the species which have been examined exhibit an entire absence of the median septum in the brachial valve.

ALLORHYNCHUS N. GEN.

ALLORHYNCHUS HETEROPSIS (WINCHELL)

One of the species in which an entire absence of the brachial median septum has been observed is *Rhynchonella heteropsis* Winchell, but in its external configuration it departs so widely from the typical form of *Pugnax* that no one has ever suggested that it be considered as a member of that genus. In figure 8 a series of cross-sections of this species is

FIGURE 8.—*Cross-sections of the rostral Portion of Allorhynchus heteropsis (Winchell)*
This series of six cross-sections (× 2½) is from a specimen from the Kinderhook bed No. 4, at Burlington, Iowa

shown. The species can not be legitimately considered as a member of the genus *Pugnax* because of its external form, and on the other hand it can not be included in any of the recognized rhynchonelloid genera which it resembles externally, because of its internal features; it is therefore taken as the type of a new genus which may be called *Allorhynchus*. The species is marked by strong and angular plications which continue to the beaks of both valves, and in the umbonal portion of the brachial valve there is a distinct, median, longitudinal depression.

ALLORHYNCHUS MACRA (HALL)

Another species having the internal features of *A. heteropsis*, and lacking the external form of *Pugnax*, is *Rhynchonella macra* Hall, from the Salem limestone. A series of cross-sections of this species are shown in

FIGURE 9.—*Cross-sections of the rostral Portion of Allorhynchus macra (Hall)*
This series of four cross-sections (× 2½) is from a specimen from Salem limestone near Alton, Illinois

figure 9. The species differs from *A. heteropsis* in its much smaller size, its much more compressed form, its much shallower and more obscure fold and sinus, and in the obsolescence of the plications toward the beak.

It agrees with that species in the absence of a brachial median septum, in the short dental lamellæ of the pedicle valve, and in the presence of a median, longitudinal depression in the umbonal portion of the brachial valve.

Camarotœchia Hall and Clarke

General characteristics

In the Devonian faunas of North America the genus *Camarotœchia* has an abundant representation. The members of the genus are characterized by the presence of a median septum in the brachial valve which is divided internally to form a short crural cavity between the two sides of the divided hinge-plate. The crural cavity is commonly very short, sometimes terminating posterior to the articulation of the valves, but the simple, unattached median septum sometimes continues with gradually diminishing height, well toward the center of the valve. In the pedicle valve members of this genus are supplied with well developed dental lamellæ which join the floor of the valve independently. In their external configuration members of the genus Camarotœchia are strongly and more or less angularly plicated, the plications continuing to the beak, and they possess a well defined fold and sinus.

Camarotœchia chouteauensis n. sp.

In the Mississippian faunas a single well defined but undescribed species of Camarotœchia has been observed. It is a common form in the

FIGURE 10.—*Cross-sections of the rostral Portion of Camarotœchia chouteauensis n. sp.* This series of eight cross-sections (× 2½) is from a specimen from the Chouteau limestone of central Missouri

Chouteau limestone and may be called *C. chouteauensis*. A series of cross-sections of the species is shown in figure 10.

Wilsonia Kayser

Wilsonia grosvenori (Hall)

A species which was referred to the genus *Pugnax* by Hall and Clarke and by Schuchert is *Rhynchonella grosvenori* Hall. Internally this species possesses all the essential characters of *Camarotœchia*, as is shown in

the series of cross-sections given in figure 11. Externally it is more or less subcubical in form, with comparatively fine plications and slightly depressed median sinus in the pedicle valve, which is greatly produced anteriorly at nearly a right angle to the plane of the valve. These char-

FIGURE 11.—*Cross-sections of the rostral Portion of Wilsonia grosvenori (Hall)*

This series of five cross-sections (× 2½) is from a specimen from the Salem limestone of Illinois

acters give the species much the aspect of members of the genus *Wilsonia*, to which genus it is here provisionally referred. The internal characters of typical members of the genus *Wilsonia* differ in no essential respect from Camarotœchia, and if the genus is worthy of recognition it must be distinguished by its external form.

LEIORHYNCHUS HALL

LEIORHYNCHUS GREENEANUM (ULRICH)

Another rhynchonelloid genus recognized by Hall and Clarke, which has the essential internal characters of *Camarotœchia*, is *Leiorhynchus*. This genus is established primarily upon its external form, it being but

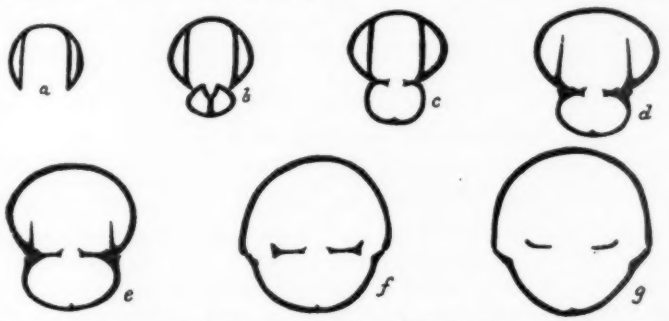

FIGURE 12.—*Cross-sections of the rostral Portion of Leiorhynchus greeneanum (Ulrich)*

This series of seven cross-sections (× 2½) is from a specimen from the Knobstone formation of southern Indiana

obscurely plicated, with its plications commonly better developed on the fold and sinus than upon the sides of the shell. A good example of this genus is *L. greeneanum* (Ulrich), from the basal Mississippian of southern Indiana, a series of cross-sections of which is shown in figure 12.

PUGNOIDES N. GEN.

PUGNOIDES OTTUMWA (WHITE)

One of the rhynchonelloid shells which has been commonly referred by recent authors to the genus *Pugnax* is *Rhynchonella ottumwa* White. A series of cross-sections of this species is reproduced in figure 13, in which it is shown to possess all the essential internal characters of *Camarotœchia*. If, however, it is legitimate to recognize such genera as *Wilsonia* and *Leiorhynchus*, genera possessing essentially the same internal structure as

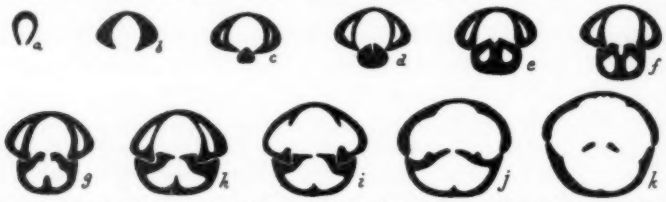

FIGURE 13.—*Cross-sections of the rostral Portion of Pugnoides ottumwa (White)*
This series of eleven cross-sections (× 2½) is from a specimen from the Pella beds of Iowa

Camarotœchia, and based primarily upon the external form and ornamentation of the shell, then *R. ottumwa*, with its external aspect of *Pugnax*, must also be excluded from *Camarotœchia*, and as there is no genus in which it can be placed, it becomes necessary to establish a new one for its reception. This genus may be called *Pugnoides*, with *P. ottumwa* as genotype.

SHUMARDELLA N. GEN.

SHUMARDELLA MISSOURIENSIS (SHUMARD)

A species of rhynchonelliform shell from the Chouteau limestone was described by Shumard in 1855 as *Rhynchonella missouriensis*. The contour and ornamentation of the shell is peculiar, and it has commonly been referred to the genus *Pugnax* by recent authors, evidently because of its coarse plications, which become more or less obsolescent toward the beak. The presence of a strong median septum in the brachial valve, however, must exclude the species from that genus, and the internal characters of the shell are so different from other species that, associated as they are with the peculiar external form, the species may be taken as the type of a new genus, *Shumardella*. A series of cross-sections of the shell is shown in figure 14. In this genus the median septum of the brachial valve is divided internally by a narrow median incision, which, however, is not open cardinally to form an open crural cavity as in *Camarotœchia*, but is arched over, as is shown in figure 14*d*. The me-

dian septum is soon disconnected from the cardinal side of the valve (figure 14*e*), and continues with gradually decreasing height well toward the middle of the valve. With the disconnection of the median septum cardinally, the two plates forming the sides of the inclosed crural cavity continue as free plates extending into the cavity of the valve (figure 14*e*),

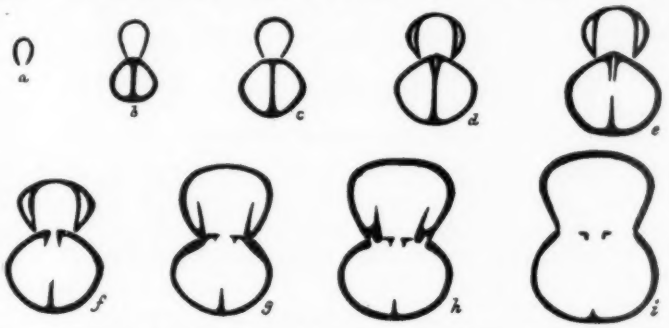

FIGURE 14.—*Cross-sections of the rostral Portion of Shumardella missouriensis (Shum.)*
This series of nine cross-sections (× 2½) is from a specimen from the Chouteau limestone of Missouri

the space between the plates is arched over cardinally for a time, but with the reduction of the width of these vertical plates the hinge-plate becomes divided just posterior to the articulation of the valves (figure 14*f*). Beyond the articulation of the valves the inner margins of the divided hinge-plate are produced anteriorly into the bases of the crura.

SHUMARDELLA OBSOLESCENS (HALL)

Associated with *S. missouriensis* in the Chouteau limestone is a smaller, more subglobular shell, with nearly obsolete plications, which has com-

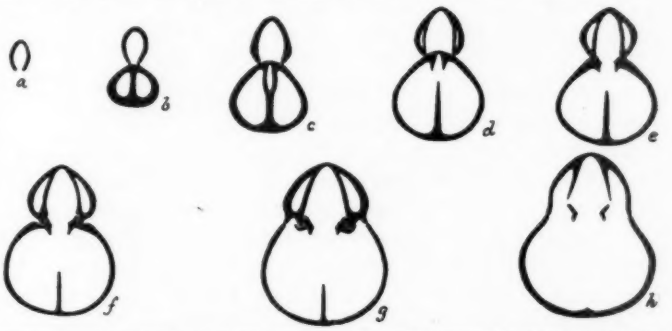

FIGURE 15.—*Cross-sections of the rostral Portion of Shumardella obsolescens (Hall)*
This series of eight cross-sections (× 2½) is from a specimen from the Chouteau limestone of Missouri

monly been considered as a variety of *S. missouriensis*. This shell is perhaps identical with *Rhynchonella obsolescens* Hall, from the Rockford limestone of Indiana; at least the external form is essentially the same, and it may be designated as *S. obsolescens* until the internal characters of the Rockford shells are investigated. A series of cross-sections of this shell is shown in figure 15, which shows that in its essential features it agrees with *S. missouriensis* and may be included in the same genus.

Rhynchopora King

GENERAL CHARACTERISTICS

The genus *Rhynchopora* has been established to include several rhynchonelloid shells which are known to possess a punctate shell structure, this shell structure being the essential character upon which the genus has been based. The internal structure of the shell has never been described, but on investigation several species seem to exhibit additional characters of generic importance. No opportunity has been afforded to examine the genotype of the genus.

RHYNCHOPORA PUSTULOSA (WHITE)

This species occurs in one of the Kinderhook formations at Burlington, Iowa, and a series of cross-sections of a typical representative of the species is shown in figure 16. After the second section the pedicle valve is

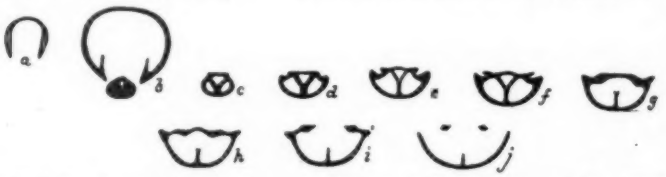

FIGURE 16.—*Cross-sections of the rostral Portion of Rhynchopora pustulosa (White)* This series of ten cross-sections (× 2½) is from a specimen from the Kinderhook bed No. 4, at Burlington, Iowa

not shown in these figures, as it possesses no features of diagnostic value. In the brachial valve a well defined median septum is present which is divided to form a crural cavity as it approaches the cardinal side of the valve (figures 16*c*, *d*, *e*, *f*), but, unlike Camarotœchia, this crural cavity is roofed over by the undivided hinge-plate. Even after the median septum has become disconnected cardinally the undivided hinge-plate persists nearly to the point where the crusal bases become free (figures 16*g*, *h*, *i*). This character of the undivided hinge-plate is entirely different from any other generic group of Mississippian rhynchonelloids

which has been investigated in these studies, and seems to be an additional character of generic value in *Rhynchopora*.

RHYNCHOPORA HAMBURGENSIS N. SP.

In the thin oolite limestone of the Kinderhook at Hamburg, Illinois,[10] a small rhynchonelloid shell occurs in great profusion. The shell structure is distinctly punctate and a series of cross-sections, reproduced in

FIGURE 17.—*Five Cross-sections of the rostral Portion of the Pedicle Valve and Six of the Brachial Valve of Rhynchopora hamburgensis n. sp.*

These two series of cross-sections (× 2½) are from specimens from the Kinderhook oolite of Hamburg, Illinois

figure 17, shows that it has the same type of undivided hinge-plate as is present in *R. pustulosa*.

RHYNCHOPORA BEECHERI GREGER

Cross-sections of this shell have not been made, but a series of very excellent internal casts in chert exhibit not only its strongly punctate shell structure, but also the presence of an undivided hinge-plate similar to that in other members of the genus.

RHYNCHOPORA PERSINUATA (WINCHELL)

This species has not previously been referred to the genus *Rhynchopora*, but study of an excellent example of an internal cast of the species from the typical locality shows that the hinge-plate is undivided as in members of the genus, but the specimen is not preserved in such a manner as to exhibit either the presence or absence of the characteristic punctate shell structure. On examining all available examples of the species, however, one was observed in which the shell structure is distinctly punctate, so that the two essential characteristics of the genus *Rhynchopora* are known to be present.

RHYNCHOPORA ? COOPERENSIS (SHUMARD)

This species occurs somewhat commonly in the Chouteau limestone, but a diligent examination of all the examples which have been available for study has failed to demonstrate that the punctate structure of the

[10] Transactions of the Academy of Science of Saint Louis, vol. xvi, p. 465.

shell is present; but in its external features the shell is so like *R. persinuata* that the two species can scarcely be distinguished. A series of cross-sections showing the internal features of the species is reproduced in figure 18, and these show the characteristic undivided hinge-plate of

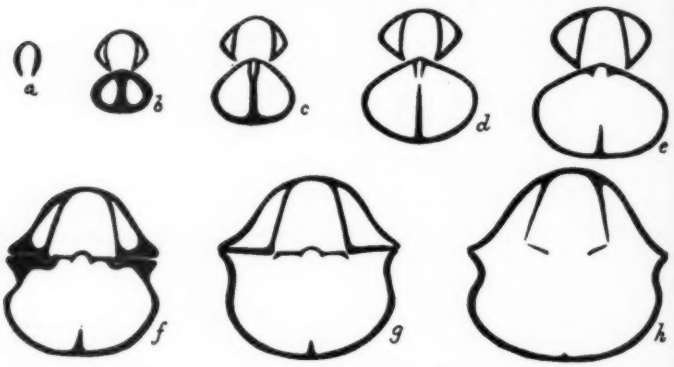

FIGURE 18.—*Cross-sections of the rostral Portion of Rhynchopora ? cooperensis (Shumard)*

This series of eight cross-sections is from a specimen from the Chouteau limestone of Missouri

Rhynchopora. Under these circumstances it seems to be safe to refer the species to that genus, although until the punctate shell structure has been observed the reference may be made with a query.